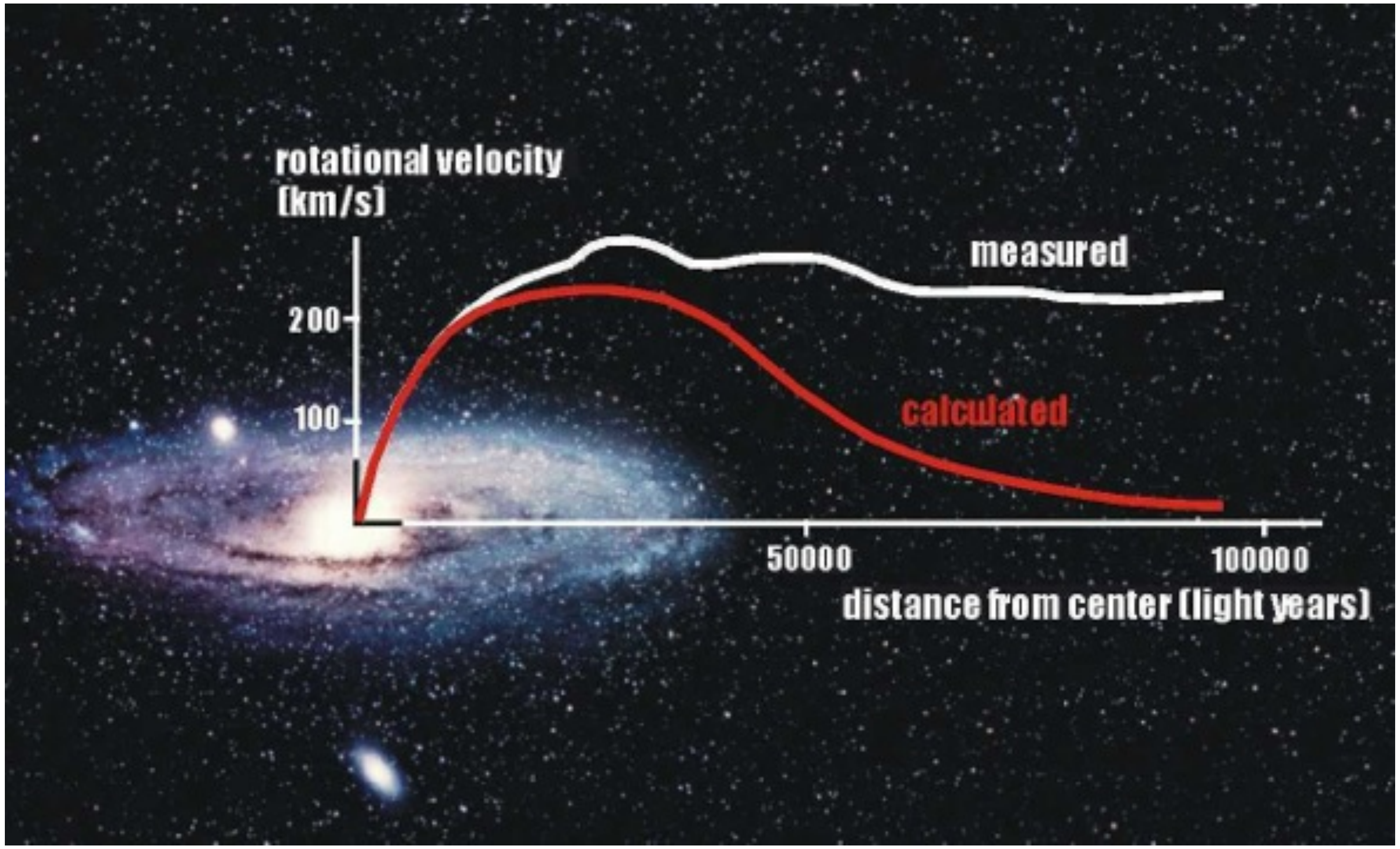
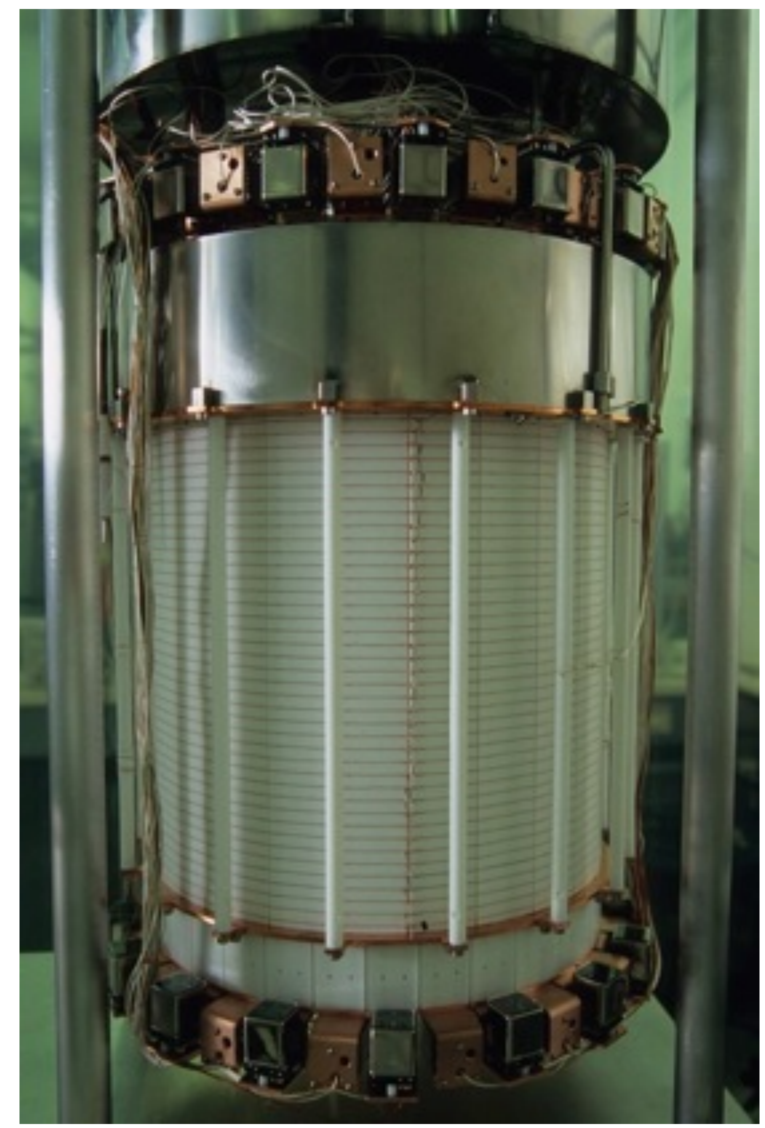
Third Generation Flavored Dark Matter

Tongyan Lin
University of Chicago

July 3, 2014
Santa Fe Workshop





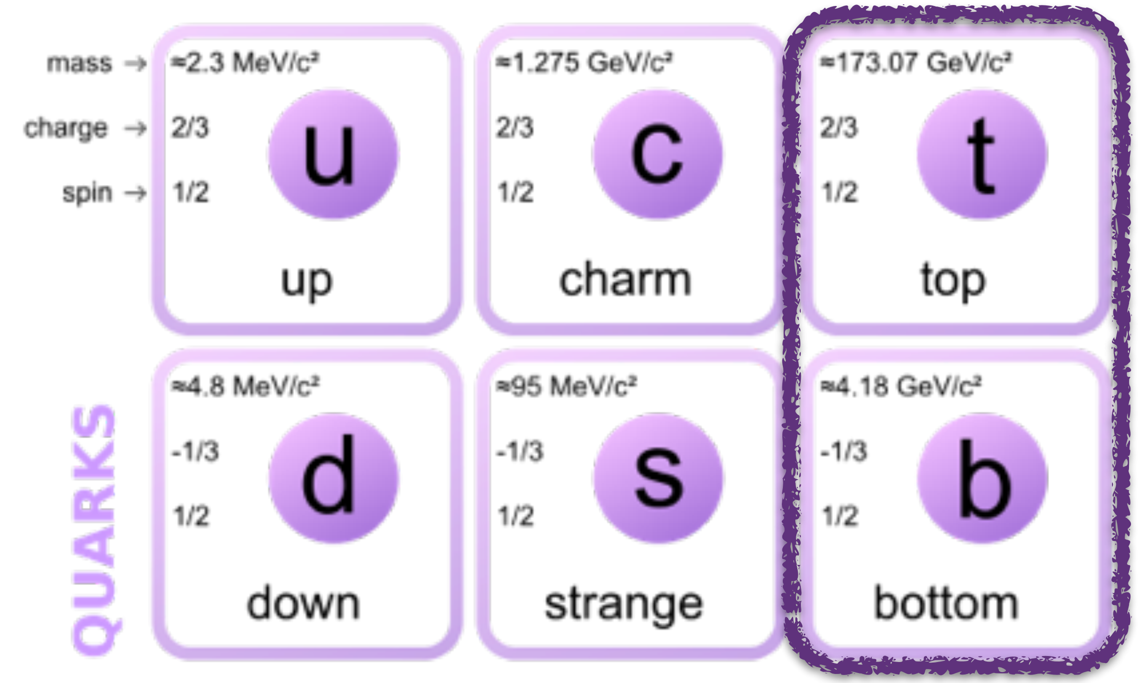
where is the dark matter?

why isn't it lighting up
direct detection experiments?

turning to the third generation:

- coupling DM to the third generation suppresses proton elastic scattering
- tagging at colliders
- indirect signals remain

- flavored DM: large yukawas can lead to large mass splittings and hierarchy in couplings



based on: Batell, Lin and Wang; Agrawal, Batell, Hooper, Lin

for third-gen lepton, see Agrawal, Chacko, et al.

outline

- MFV dark matter and RPV SUSY
- top-flavored dark matter
- bottom-flavored dark matter
    - as a model for the Galactic Center excess

flavored dark matter

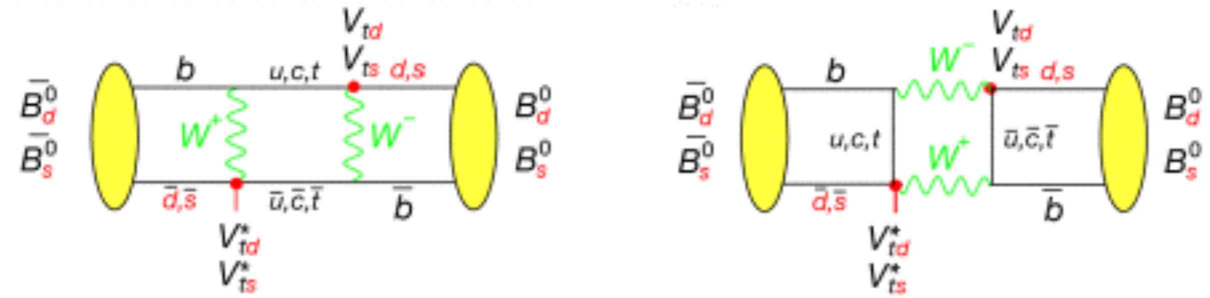
Flavor symmetry of the SM:

$$SU(3)_Q \times SU(3)_u \times SU(3)_d$$

Broken by Yukawas $\quad Y_u \bar{Q} H^\dagger u_R + Y_d \bar{Q} H d_R$

Additional sources of flavor/CP violation are highly constrained. Problem for models of BSM physics!

Minimal Flavor Violation: to get around constraints, assume no <u>new</u> sources of flavor violation - only Yukawas



$$Q \sim (3,1,1)$$
$$\bar{u} \sim (1,\bar{3},1)$$
$$\bar{d} \sim (1,1,\bar{3})$$

Introduce a dark matter multiplet (gauge singlet) transforming under SM flavor symmetry

$$Y_u \sim (\bar{3},3,1)$$
$$Y_d \sim (\bar{3},1,3)$$

$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$$

MFV DM: dark matter multiplet couples to SM quarks, respecting flavor symmetry. (Alternatively, the DM x SM flavor symmetry is broken in a way very close to MFV limit.)

Use assumption of MFV to stabilize the dark matter

Batell, Pradler, and Spannowsky

Consider a higher-dimension operator that could lead to DM decay:

$$\mathcal{O}_{\rm decay} = \chi \underbrace{Q\ldots}_{A}\underbrace{\bar{Q}\ldots}_{B}\underbrace{u_R\ldots}_{C}\underbrace{\bar{u}_R\ldots}_{D}\underbrace{d_R\ldots}_{E}\underbrace{\bar{d}_R\ldots}_{F} \times \underbrace{Y_u\ldots}_{G}\underbrace{Y_u^\dagger\ldots}_{H}\underbrace{Y_d\ldots}_{I}\underbrace{Y_d^\dagger\ldots}_{J}\mathcal{O}_{\rm weak},$$

requiring gauge-invariance and assuming MFV leads to the conditions on the DM multiplet.

$$(n-m) \bmod 3 \neq 0$$

$$n \equiv n_Q - n_u - n_d, \quad m \equiv m_Q - m_u - m_d$$

$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$$

dark matter stability

flavor triality

$$U \equiv \left(e^{4\pi i/3}\right)_{\text{color}} \times \left(e^{2\pi i/3}\right)_Q \times \left(e^{2\pi i/3}\right)_u \times \left(e^{2\pi i/3}\right)_d$$

SM quarks, Yukawas neutral under flavor triality

If DM charged, lightest flavor is stable

(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$	Yes
$(0,1)$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$	Yes
(2,0)	$(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$ $(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$	Yes
(0,2)	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{6}})$ $(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\bar{\mathbf{3}},\bar{\mathbf{3}})$	Yes
(1,1)	$(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$ $(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})$ $(\bar{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{3})$	

There is a nice way that MFV DM fits in with SUSY with R-Parity Violation:

R-Parity Violation:

$$W' = \lambda L L \bar{e} + \lambda' L Q \bar{d} + \lambda'' \bar{u} \bar{d} \bar{d} + \mu' L H_u$$

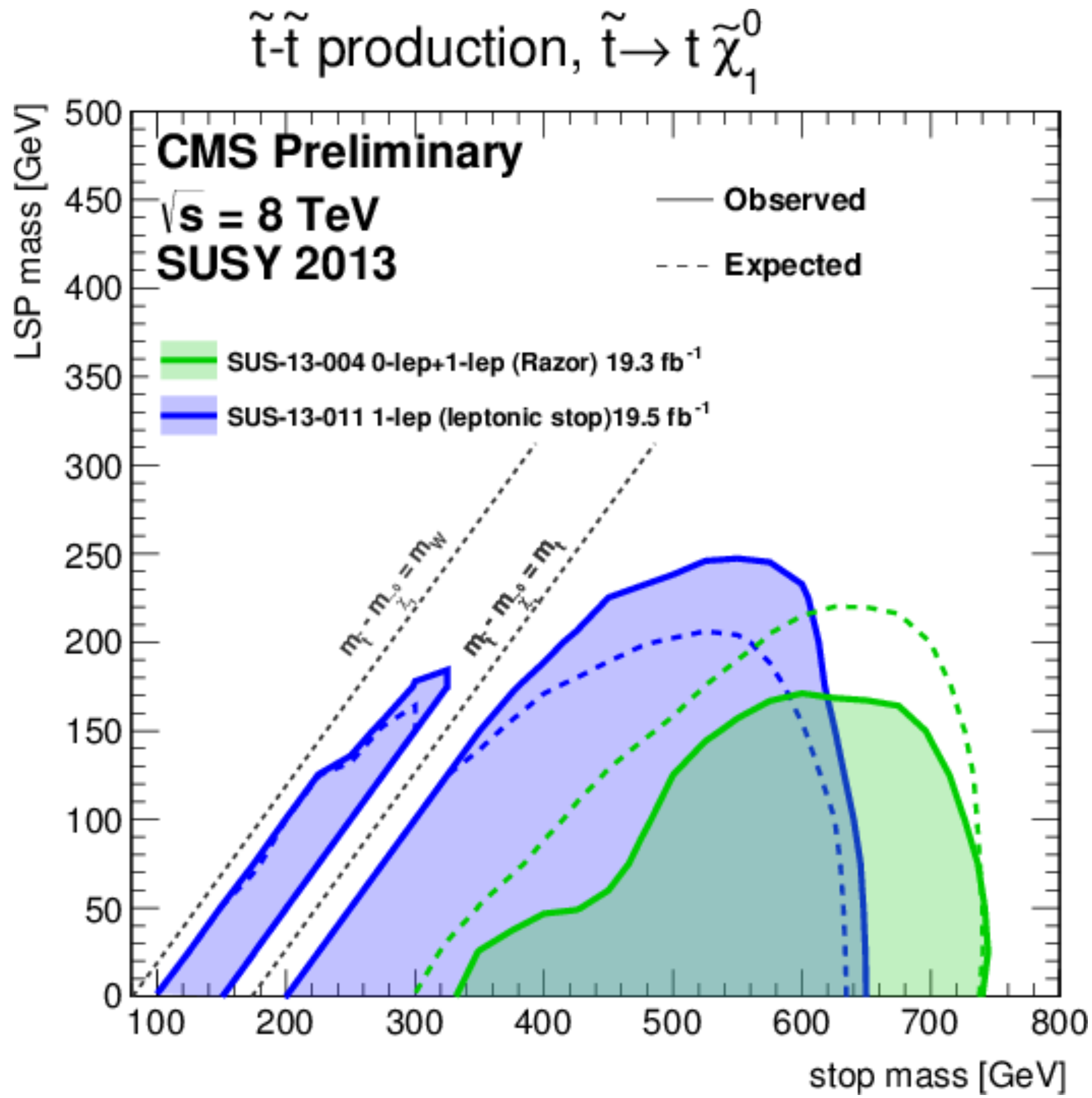
+ soft terms

- Many (small) parameters
- LSP decay - no neutralino DM
- Proton decay constraint:

$$\tau_p \sim 10^{33} \mathrm{yr} \left(\frac{10^{-19}}{\lambda'}\right)^2 \left(\frac{10^{-8}}{\lambda''}\right)^2 \left(\frac{m_{\tilde{q}}}{\mathrm{TeV}}\right)^4$$

R-parity sounds more attractive - but where are the superpartners?

stop constraints

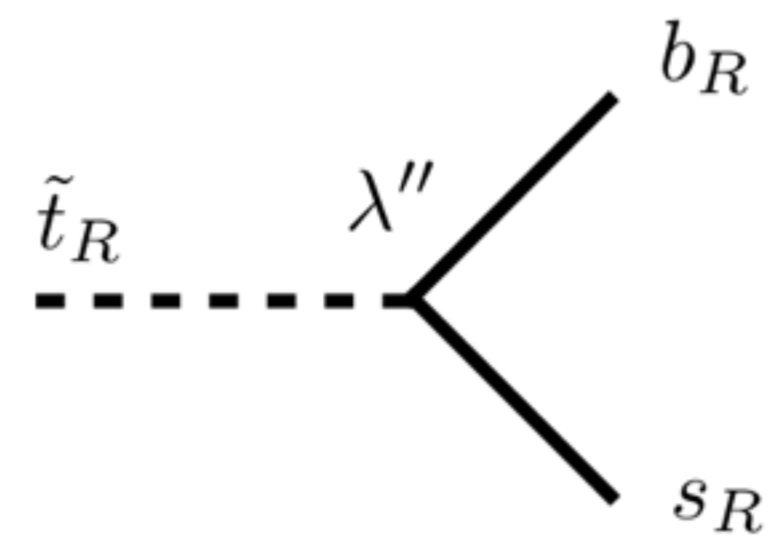


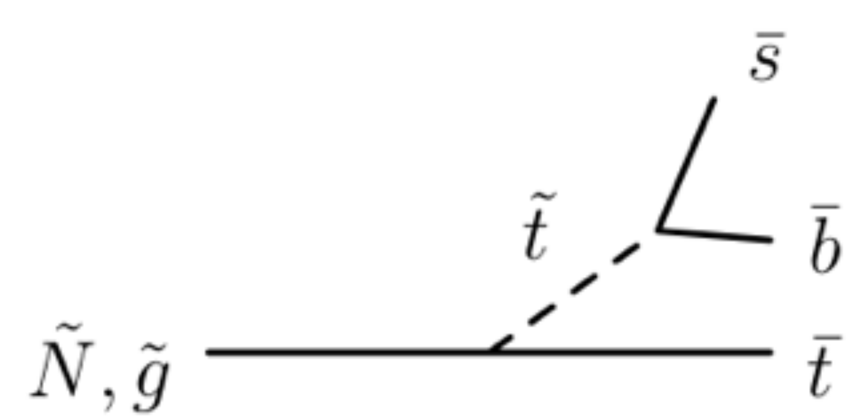
[Csaki, Grossman, Heidenreich]

MFV SUSY requires RPV superpotential consistent with MFV, and *holomorphic* in Yukawas:

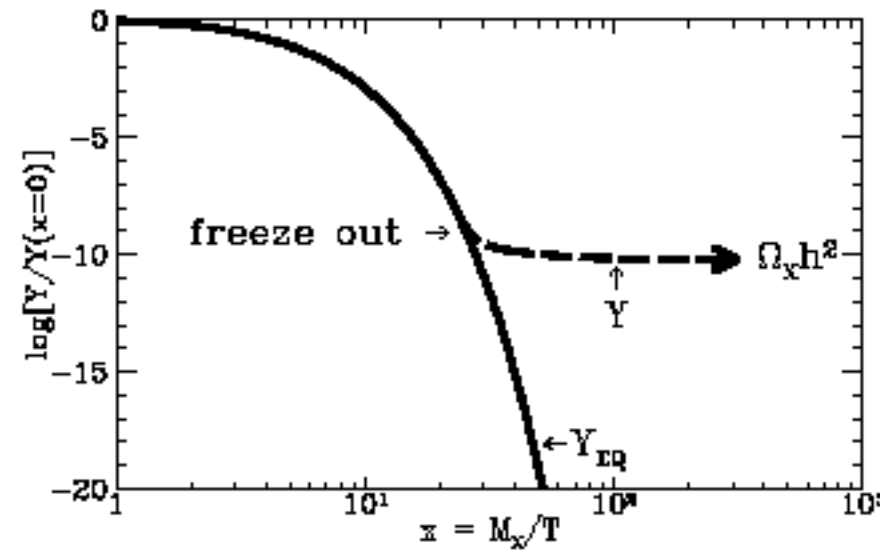
$$W' = w''(Y_u \bar{u})(Y_d \bar{d})(Y_d \bar{d})$$

- Explains size of RPV couplings
- Get around MET collider constraints
- Some form of flavor protection needed anyway
- OK with $\Delta B \neq 0$ constraints
- Holomorphic: simplification from allowing all MFV couplings



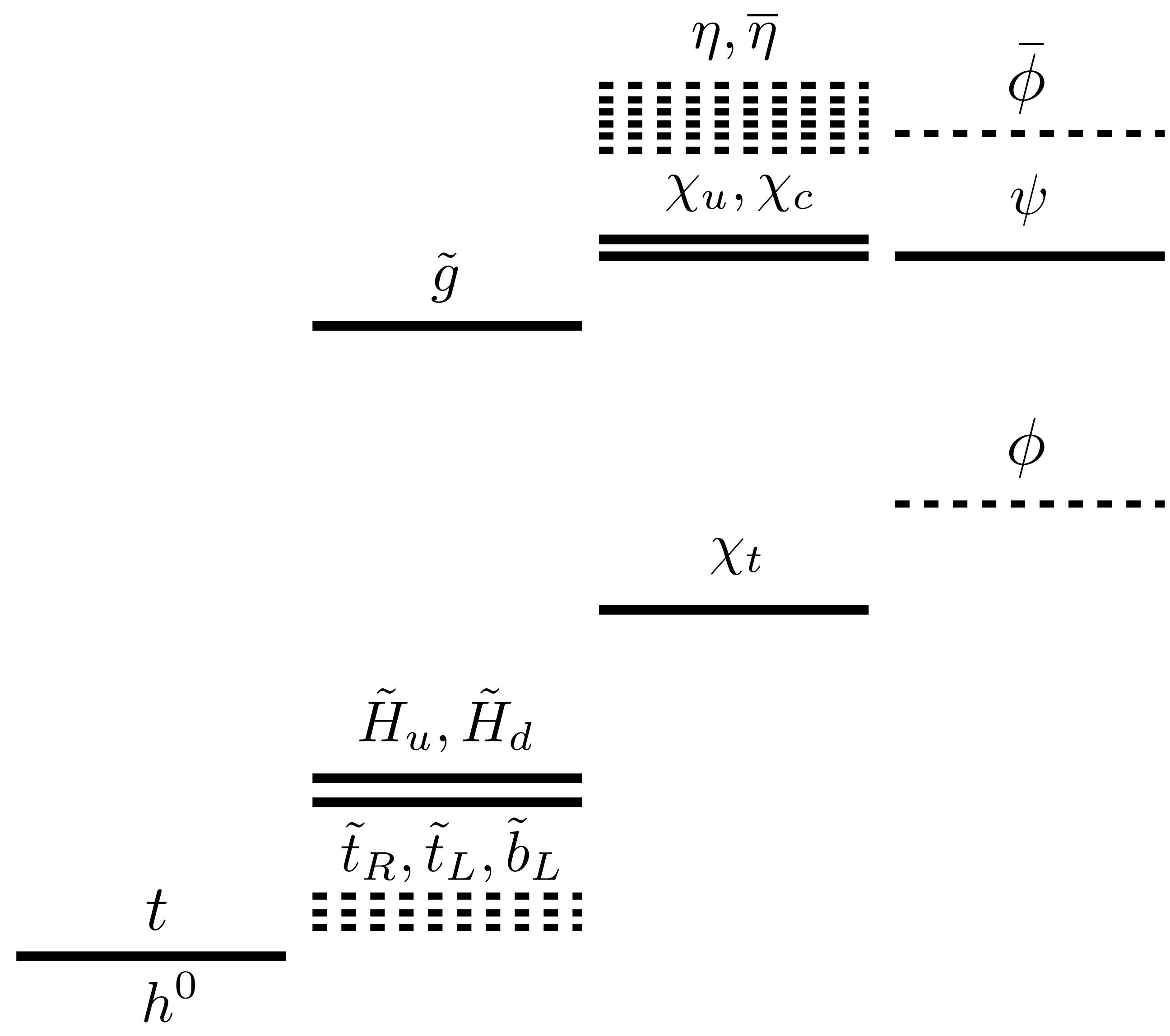


super-flavored dark matter



- restore weak-scale matter, take advantage of MFV for dark matter stability

- accommodated within RPV SUSY with light superpartners



DM flavor multiplet, colored mediator Y

$$W = \lambda Y X_i \bar{u}_R^i + M_X \bar{X} X + M_Y \bar{Y} Y$$

flavor triality

$$X_i = (\eta_i, \chi_i) \sim (1,1,0)_{\mathrm{SM}} \times (1,3,1)_{G_q}$$
$$Y = (\phi, \psi) \sim (3,1,2/3)_{\mathrm{SM}} \times (1,1,1)_{G_q}$$

$$e^{2\pi i/3}$$
$$e^{4\pi i/3}$$

Kahler potential will introduce corrections

$$\int d^4\theta \left(X^\dagger (1 + k Y_u^\dagger Y_u + \ldots) X\right)$$

$$\int d^4\theta \left(\frac{S^\dagger}{M} \bar{X} \hat{\mu}_X X + \text{h.c.}\right), \quad \hat{\mu}_X = \mu_0 + \mu_1 Y_u^\dagger Y_u + \ldots$$

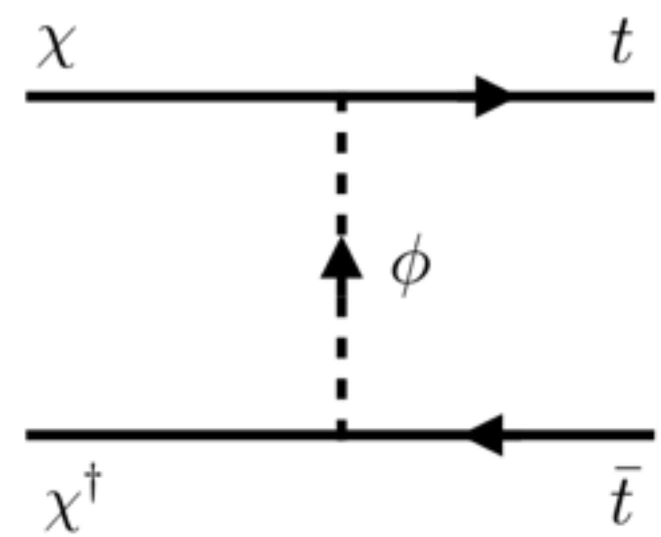
$$S = \theta^2 F$$

masses from SUSY breaking

top-flavored dm

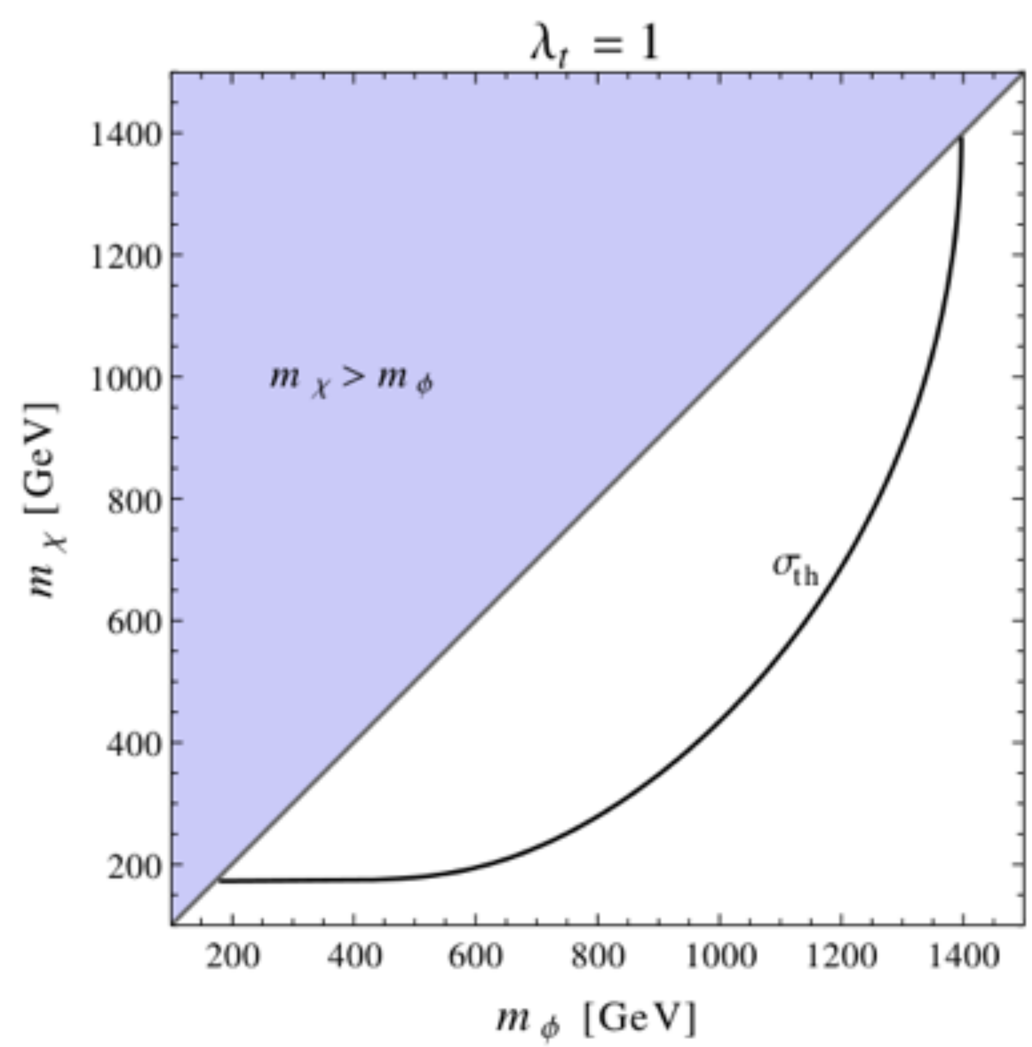
preferred coupling to tops

$$\lambda \to \lambda_0 Z_X \approx \left(\lambda_0, \lambda_0, \frac{\lambda_0}{\sqrt{1 + k y_t^2}} \right)$$



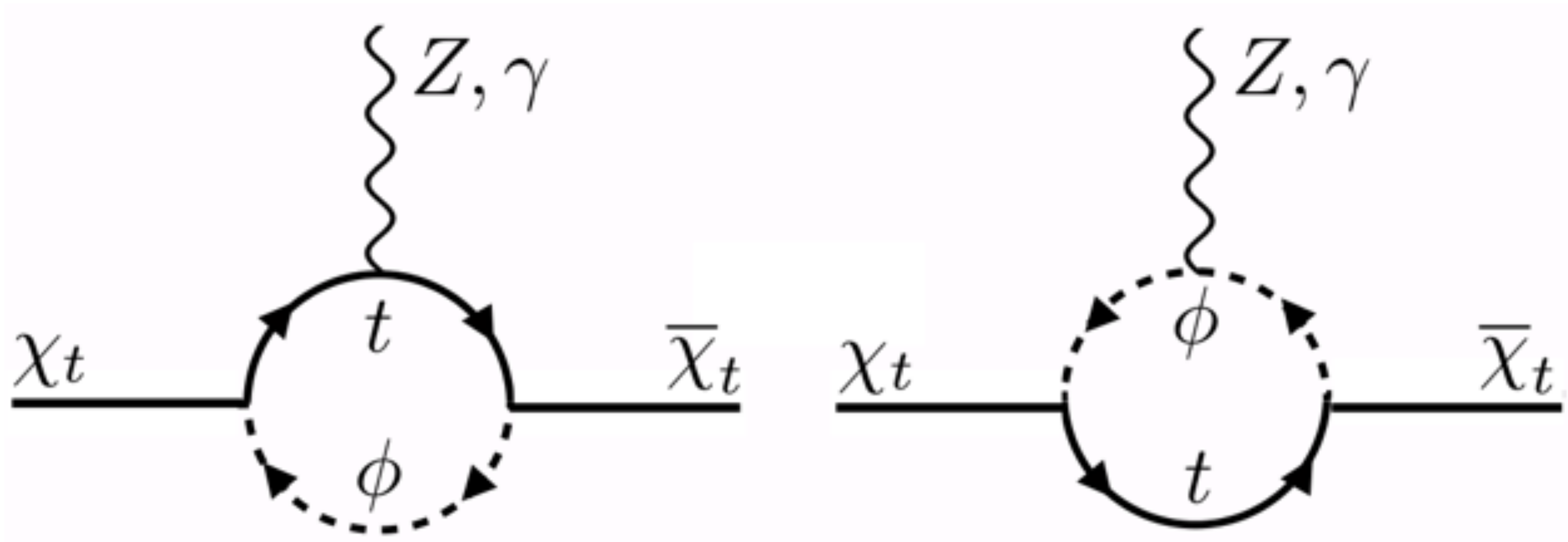
split spectrum

$$\mathcal{M}_X \approx \left(m, m, \frac{m + (F/M)\mu_1 y_t^2}{(1 + k y_t^2)} \right)$$



$$-\mathcal{L} \supset \lambda_t \bar{t}_R \chi_t \phi + \lambda_t \tilde{t}_R^\dagger \chi_t \psi + \text{h.c.}$$

direct detection through loops



coupling to Z dominates, through large top mass

$$g_Z \bar{\chi}_t \gamma^\mu P_L \chi_t Z_\mu$$

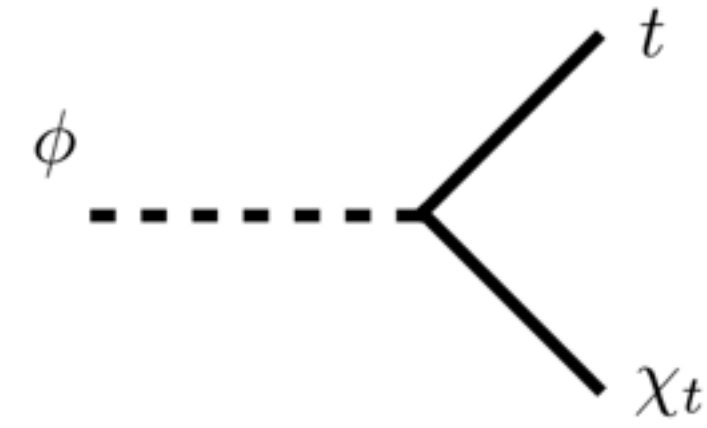
$$\mathcal{O} \sim \bar{\chi}_t \gamma^\mu P_L \chi_t H^\dagger i D_\mu H \qquad g_Z \sim \frac{g}{c_w} \frac{\lambda_t^2 N_c}{16\pi^2} \left(\frac{m_t}{m_\phi}\right)^2 \left(1 + \log \frac{m_t^2}{m_\phi^2}\right)$$

magnetic dipole moment

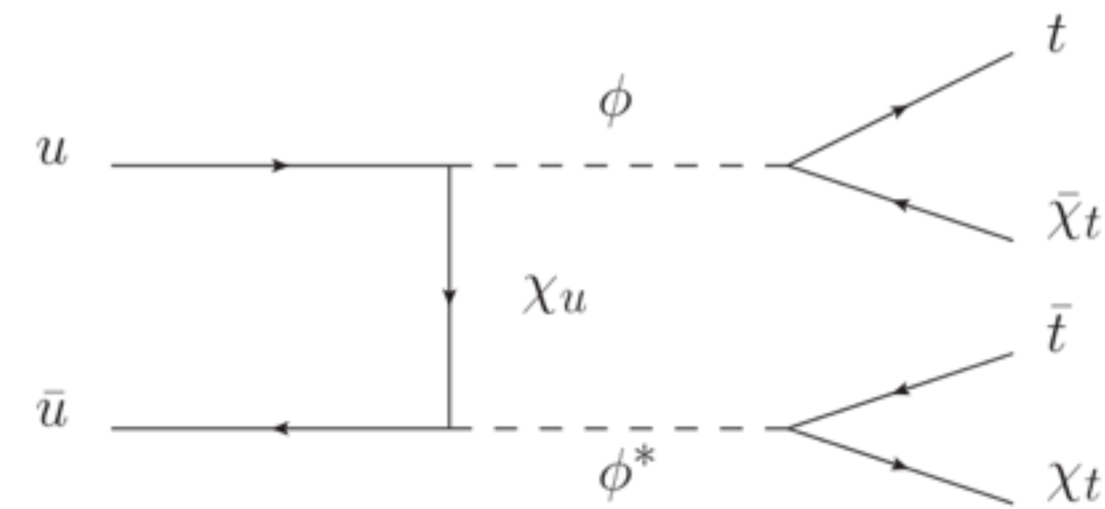
$$\frac{\mu_\chi}{2} \bar{\chi}_t \sigma^{\mu\nu} \chi_t F_{\mu\nu}$$

collider production

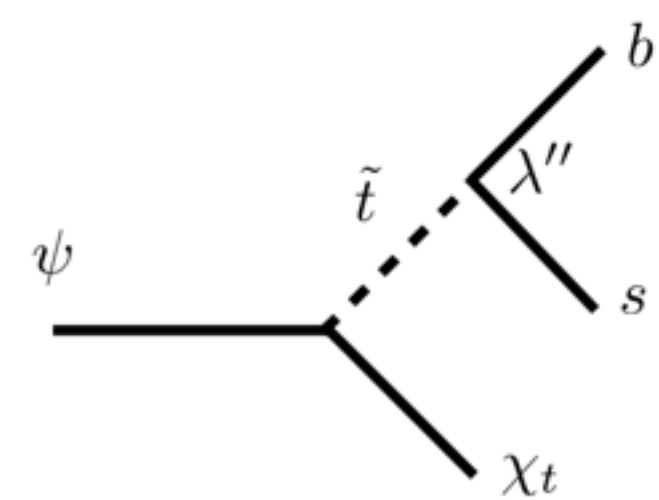
The new scalar mediator can be a “fake” stop, but its mass not tied to naturalness

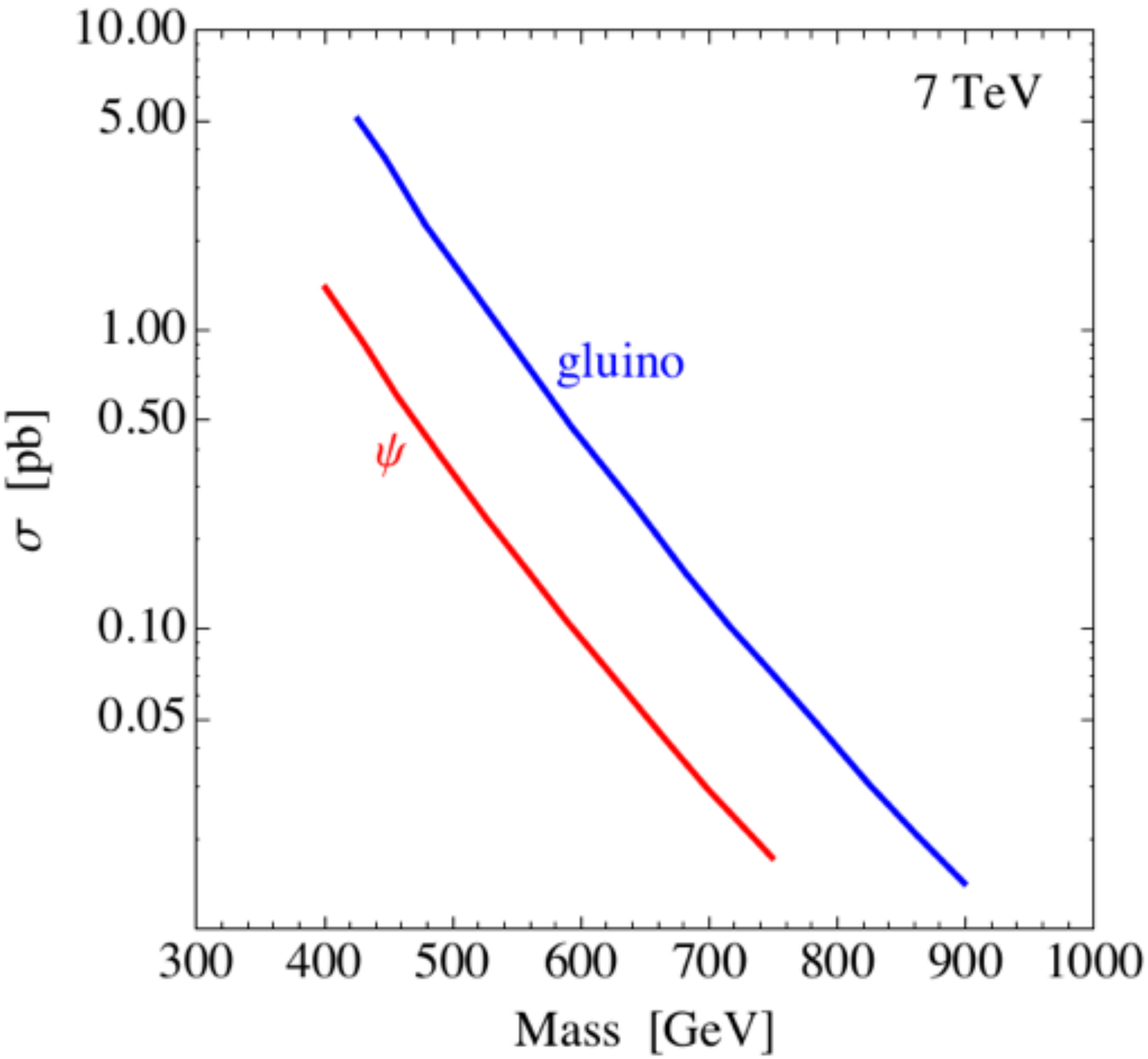


possibly other states in the t-channel:

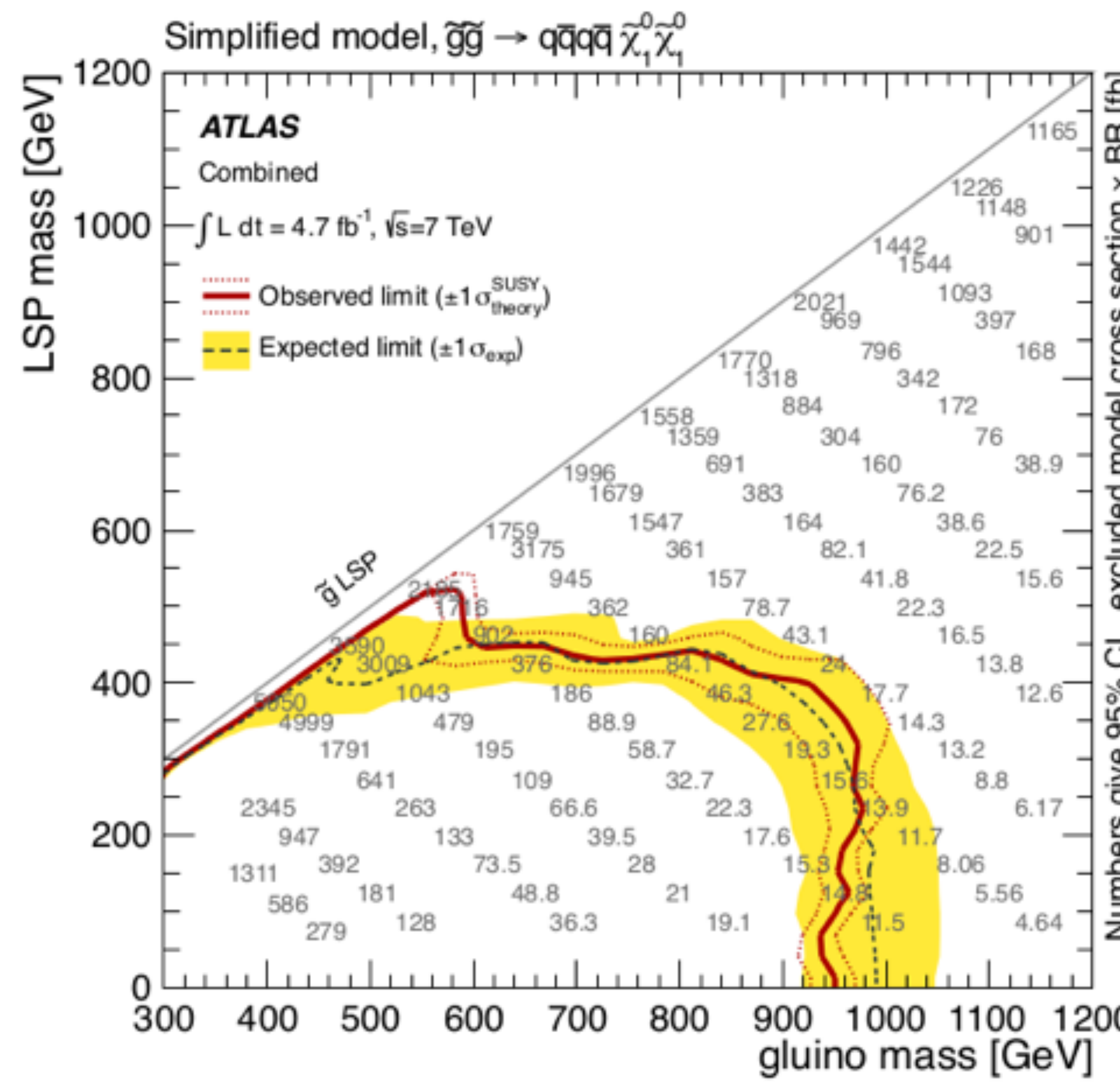


scalar triplet, gluino-like weakly constrained



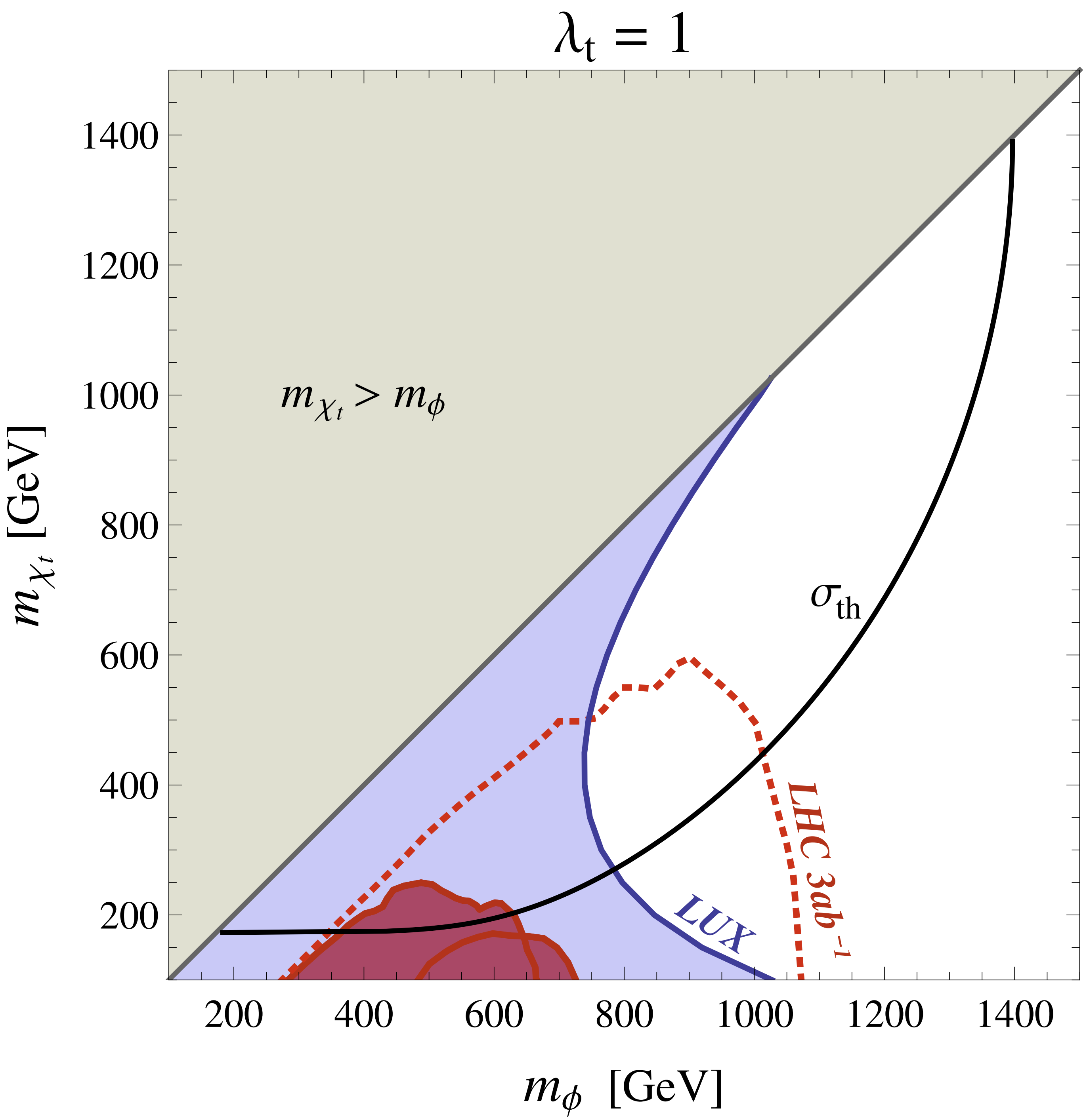


7 TeV
gluino
ψ
σ [pb]
Mass [GeV]



Simplified model, $\tilde{g}\tilde{g} \rightarrow q\bar{q}q\bar{q}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$
ATLAS
Combined
$\int L\,dt = 4.7\ \mathrm{fb}^{-1}$, $\sqrt{s}$=7 TeV
Observed limit ($\pm 1\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$)
Expected limit ($\pm 1\sigma_{\mathrm{exp}}$)
$\tilde{g}$ LSP
LSP mass [GeV]
gluino mass [GeV]
Numbers give 95% CL_s excluded model cross section × BR [fb]

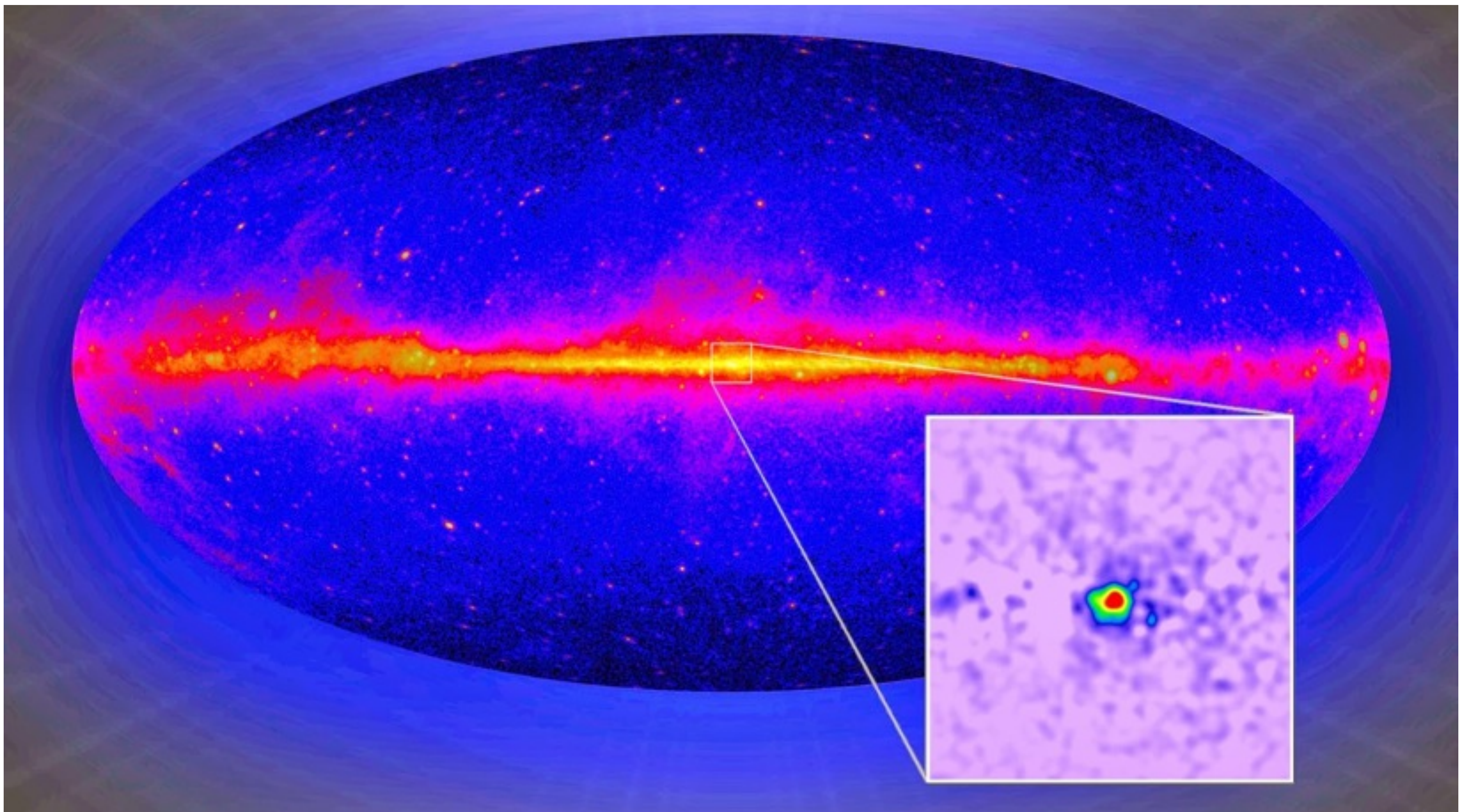
the model is alive:



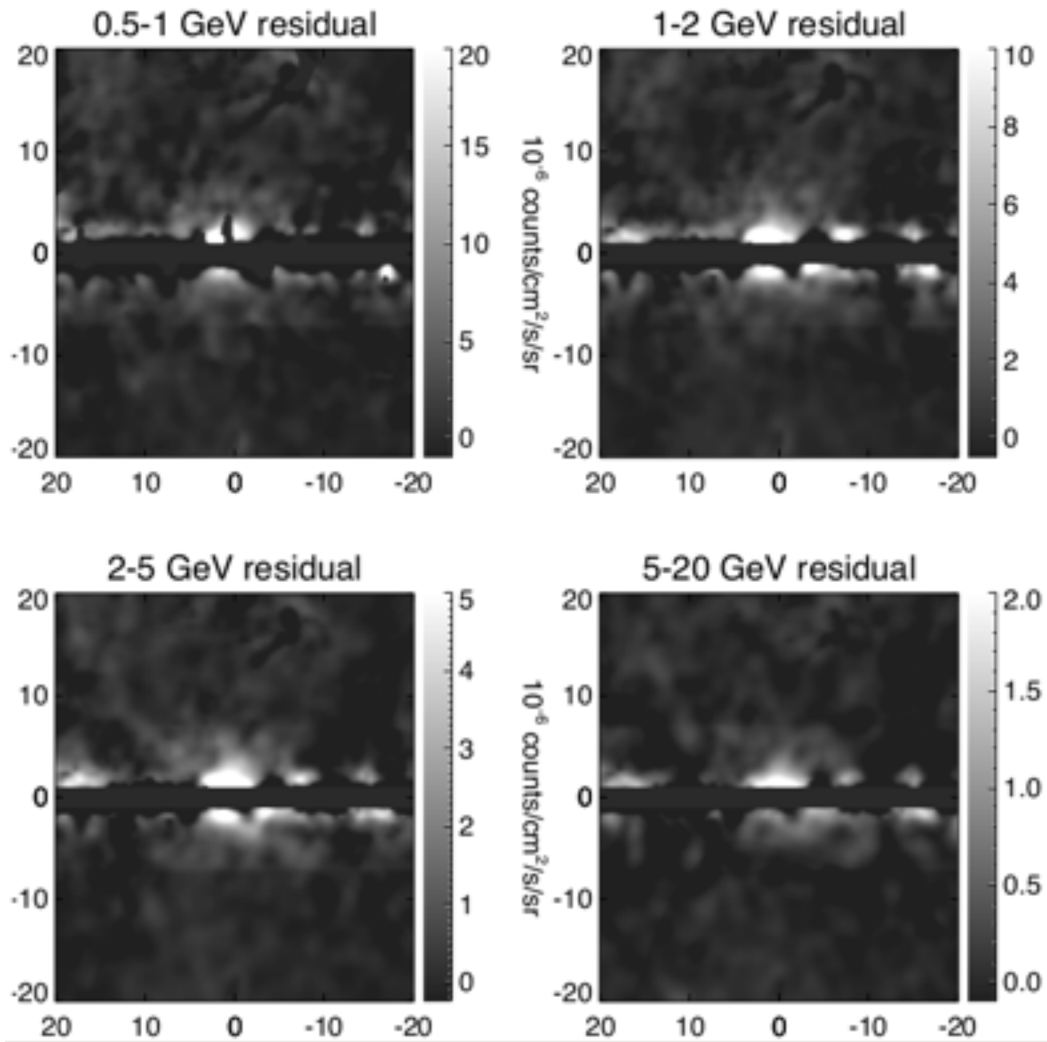
<u>Thermal relic:</u>
O(1) couplings, close to TeV scale masses to satisfy LUX constraints

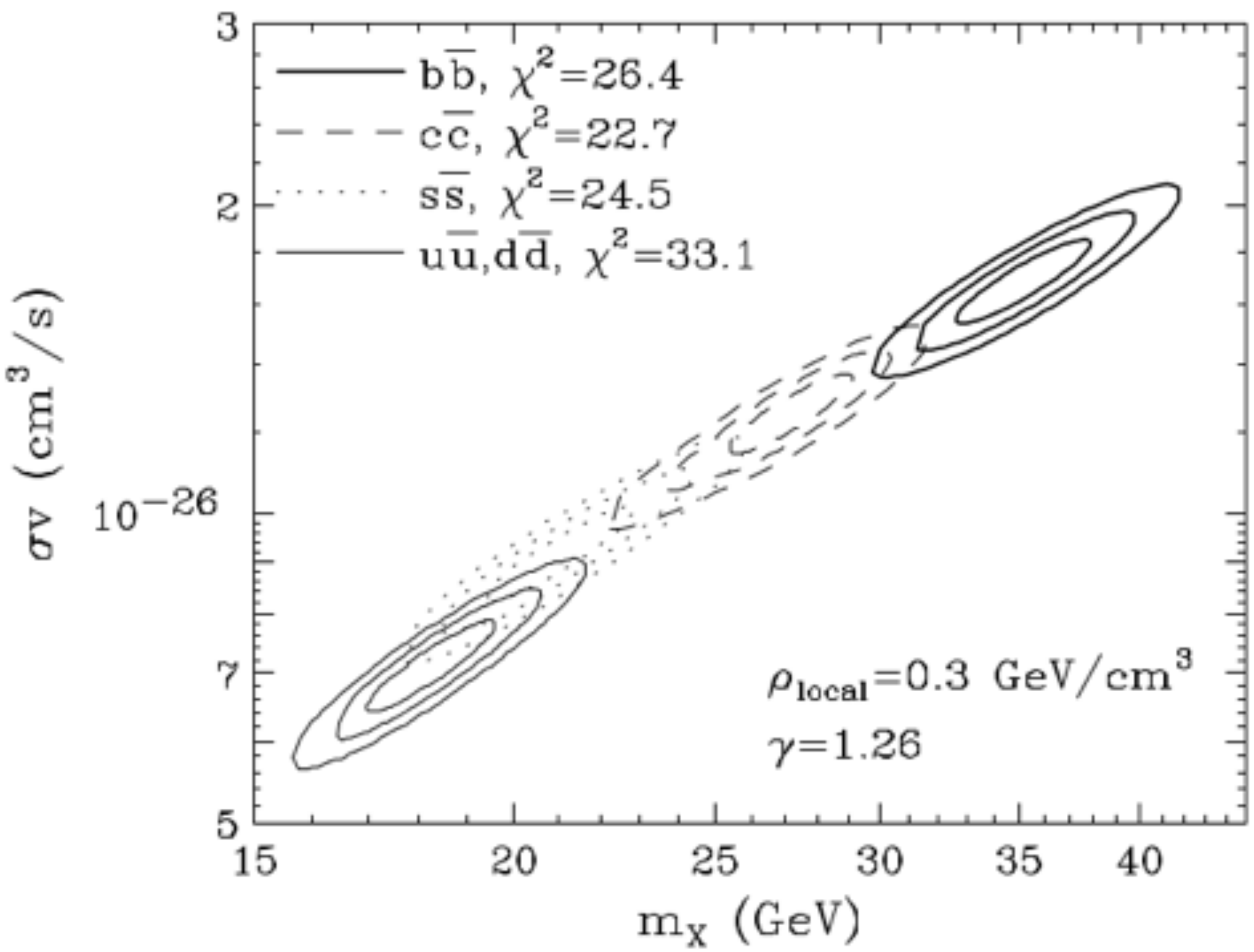
bottom-flavored dm

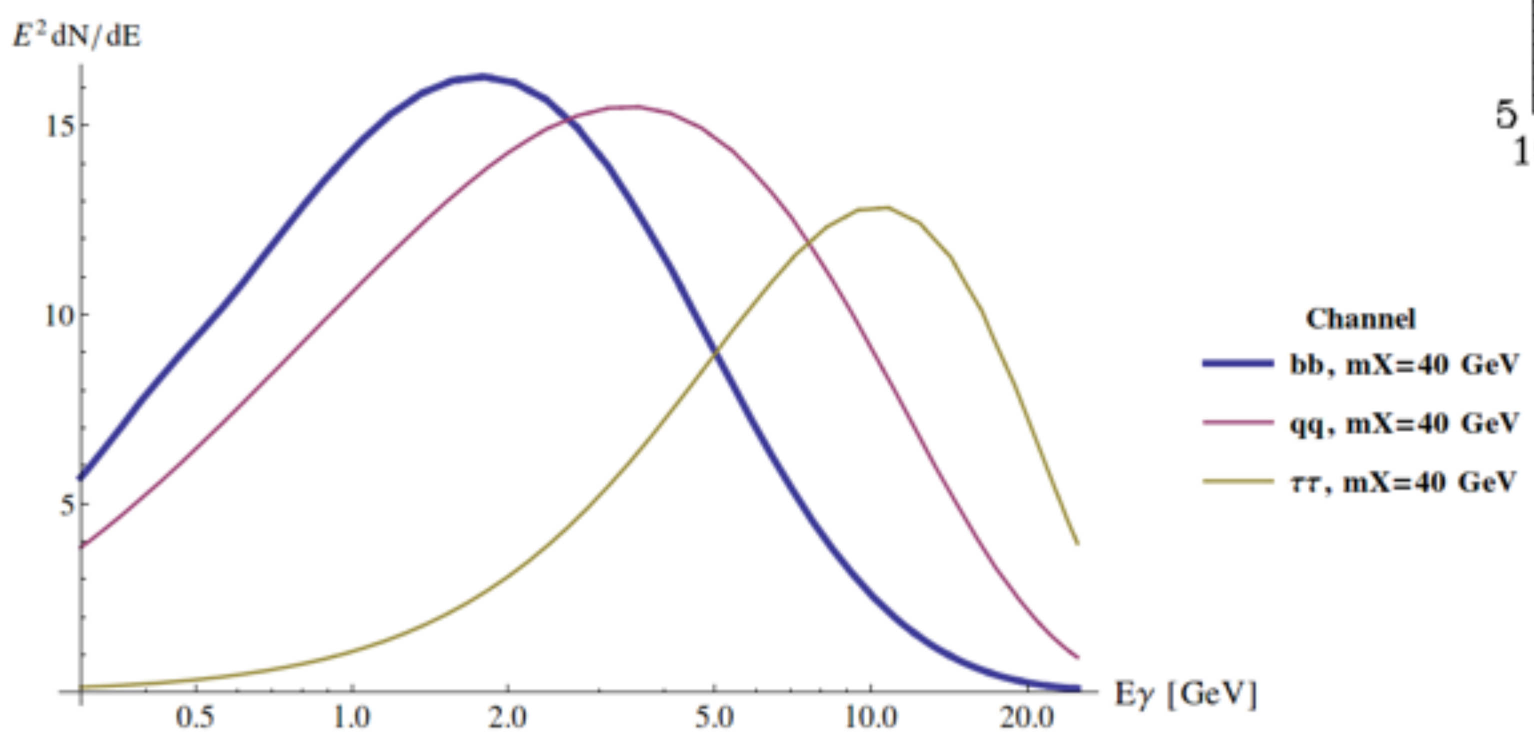
motivation: explanation of the GC excess



a dark matter gamma-ray signal?







Daylan et al.

Coupling dark matter to down-type quarks:

$$\mathcal{L} = [M_\chi]_{ji}\, \chi_i \chi_j^c + \lambda_{ij} \chi_i d_j^c \phi + \mathrm{h.c.}$$

Suppose dark matter is a triplet under $SU(3)_Q$

hierarchical couplings $\lambda = \lambda_0 Y_d$

large mass splittings

$$M_\chi = M_0 + \Delta M_u Y_u Y_u^\dagger + \Delta M_d Y_d Y_d^\dagger$$

Third-generation in DM χ_b could be the lightest, with large coupling to *b*-quarks

$$\mathcal{L} \supset \frac{\lambda_b}{2}\left[\bar{b}(1-\gamma_5)\chi_b\phi + \bar{\chi}_b(1+\gamma_5)b\phi^\dagger\right]$$

$m_\phi \gtrsim 700 \text{ GeV}$ — Charged mediator - flavor singlet sbottom-like

$m_{\chi_b} \approx 35 \text{ GeV}$ — Dirac DM, only couples to b

Integrating out mediator:

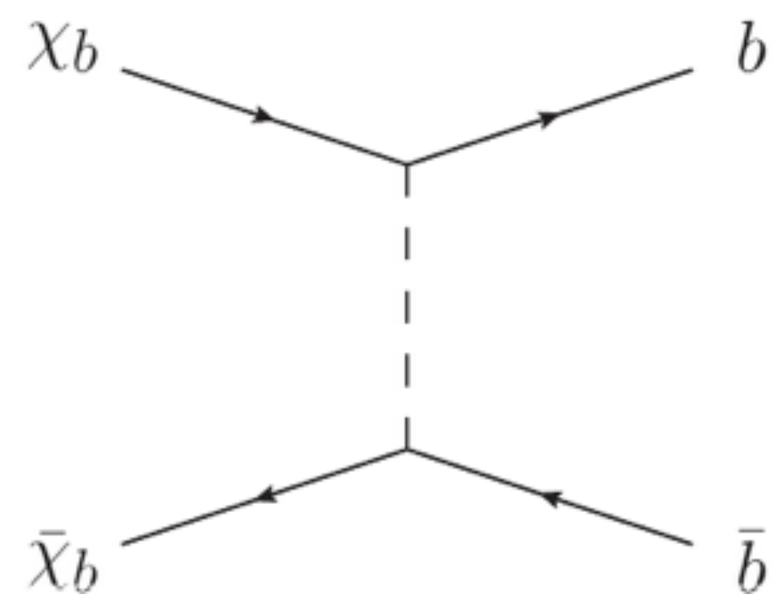
$$\mathcal{O} = \frac{\lambda_b^2}{2m_\phi^2}\bar{\chi}_b\gamma^\mu(1-\gamma_5)\chi_b\bar{b}\gamma_\mu(1+\gamma^5)b$$

Effective vector-vector and axial-axial interactions, dominant phenomenology (except collider)

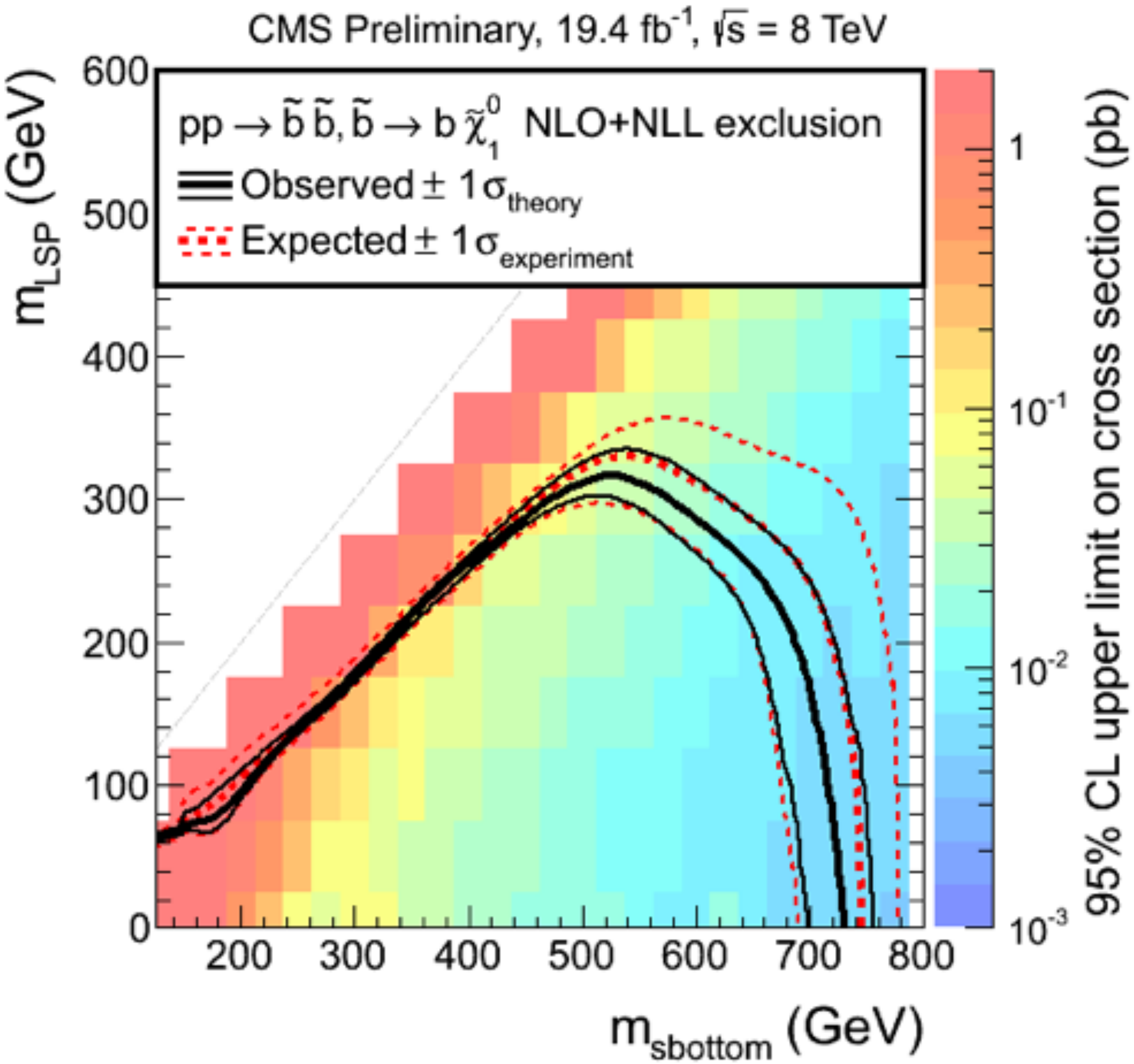
$m_\phi \gtrsim 700\ \mathrm{GeV}$

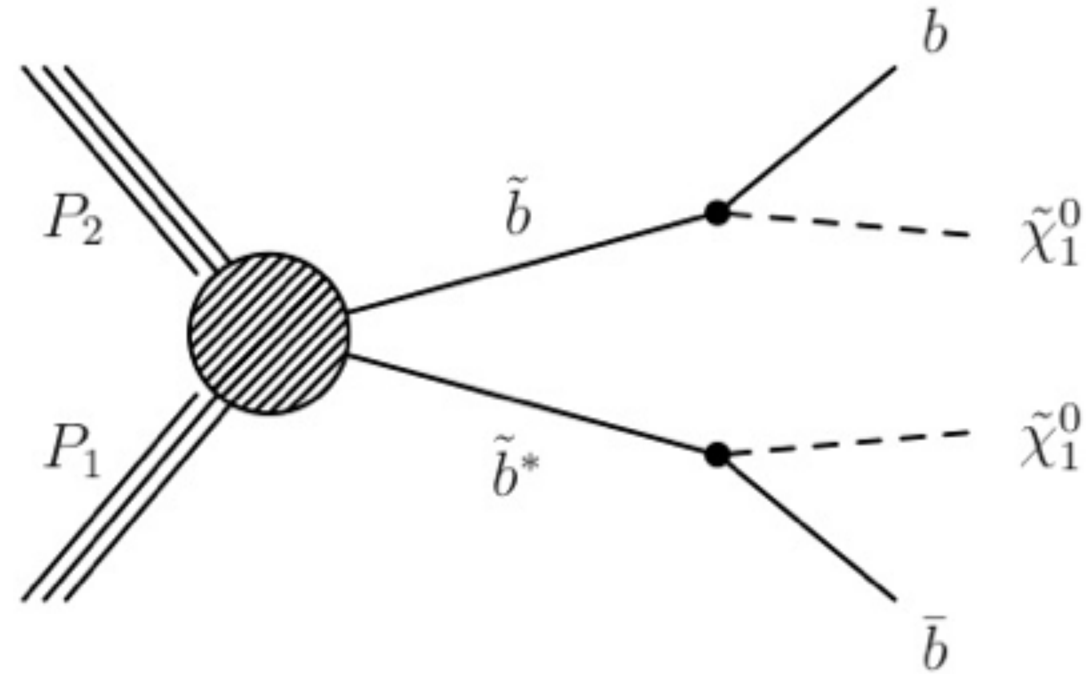
colored scalar,
strong collider constraints

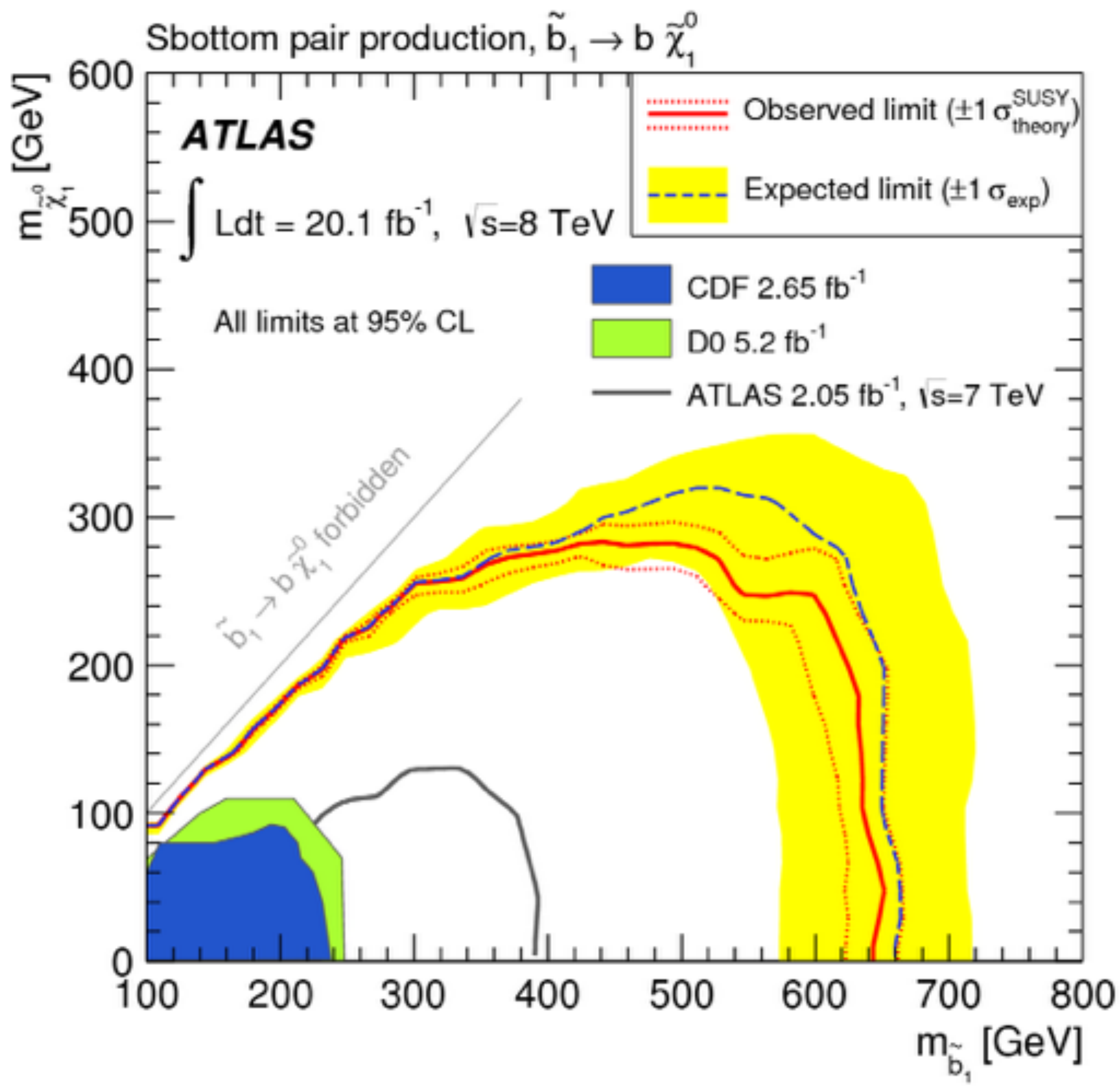
big difference in masses leads to large coupling needed for thermal relic cross section:



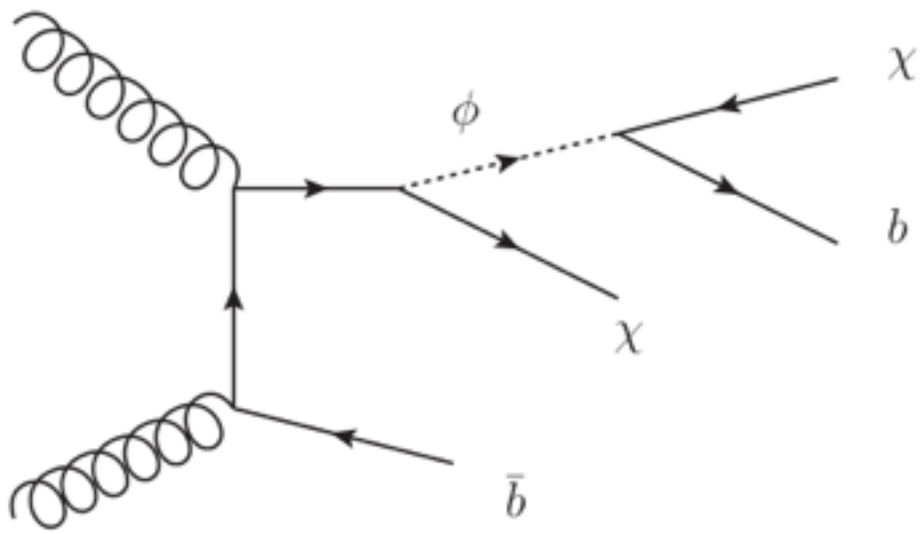
$$\sigma v = \frac{3\lambda_b^4 m_{\chi_b}^2 \sqrt{1 - m_b^2/m_{\chi_b}^2}}{32\pi (m_{\chi_b}^2 + m_\phi^2)^2} \times [1 + O(v^2)]$$
$$\approx 4.4 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{\lambda_b}{2.16}\right)^4 \left(\frac{m_{\chi_b}}{40\,\mathrm{GeV}}\right)^2 \left(\frac{725\,\mathrm{GeV}}{m_\phi}\right)^4$$

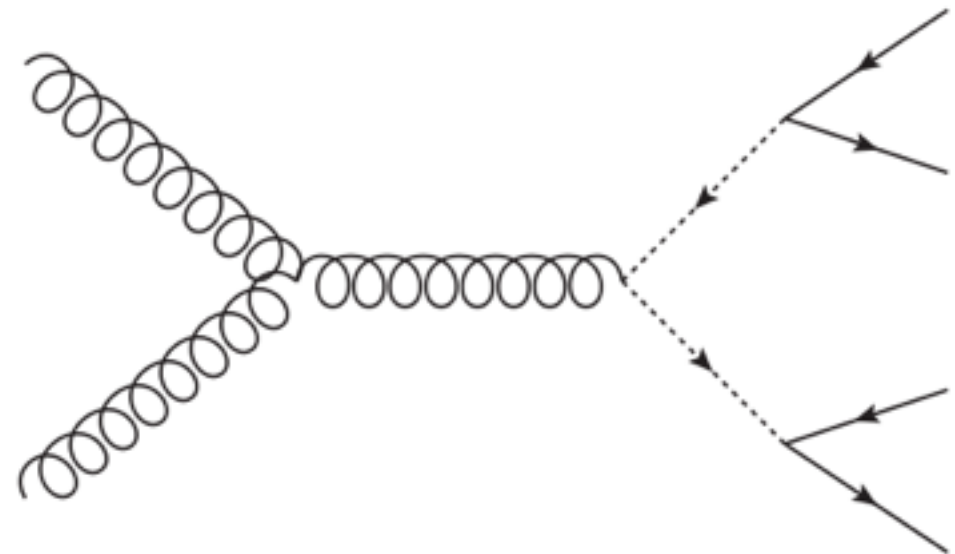

CMS Preliminary, 19.4 fb^{-1}, $\sqrt{s}$ = 8 TeV
$pp \rightarrow \tilde{b}\,\tilde{b}, \tilde{b} \rightarrow b\,\tilde{\chi}^0_1$ NLO+NLL exclusion
Observed $\pm$ 1σ_{theory}
Expected $\pm$ 1$\sigma_{experiment}$
m_{LSP} (GeV)
$m_{sbottom}$ (GeV)
95% CL upper limit on cross section (pb)


P_2
P_1
$\tilde{b}$
$\tilde{b}^*$
b
$\bar{b}$
$\tilde{\chi}^0_1$
$\tilde{\chi}^0_1$


Sbottom pair production, $\tilde{b}_1 \rightarrow b\,\tilde{\chi}^0_1$
ATLAS
$\int$ Ldt = 20.1 fb^{-1}, $\sqrt{s}$=8 TeV
All limits at 95% CL
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
CDF 2.65 fb^{-1}
D0 5.2 fb^{-1}
ATLAS 2.05 fb^{-1}, $\sqrt{s}$=7 TeV
$\tilde{b}_1 \rightarrow b\,\tilde{\chi}^0_1$ forbidden
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{b}_1}$ [GeV]

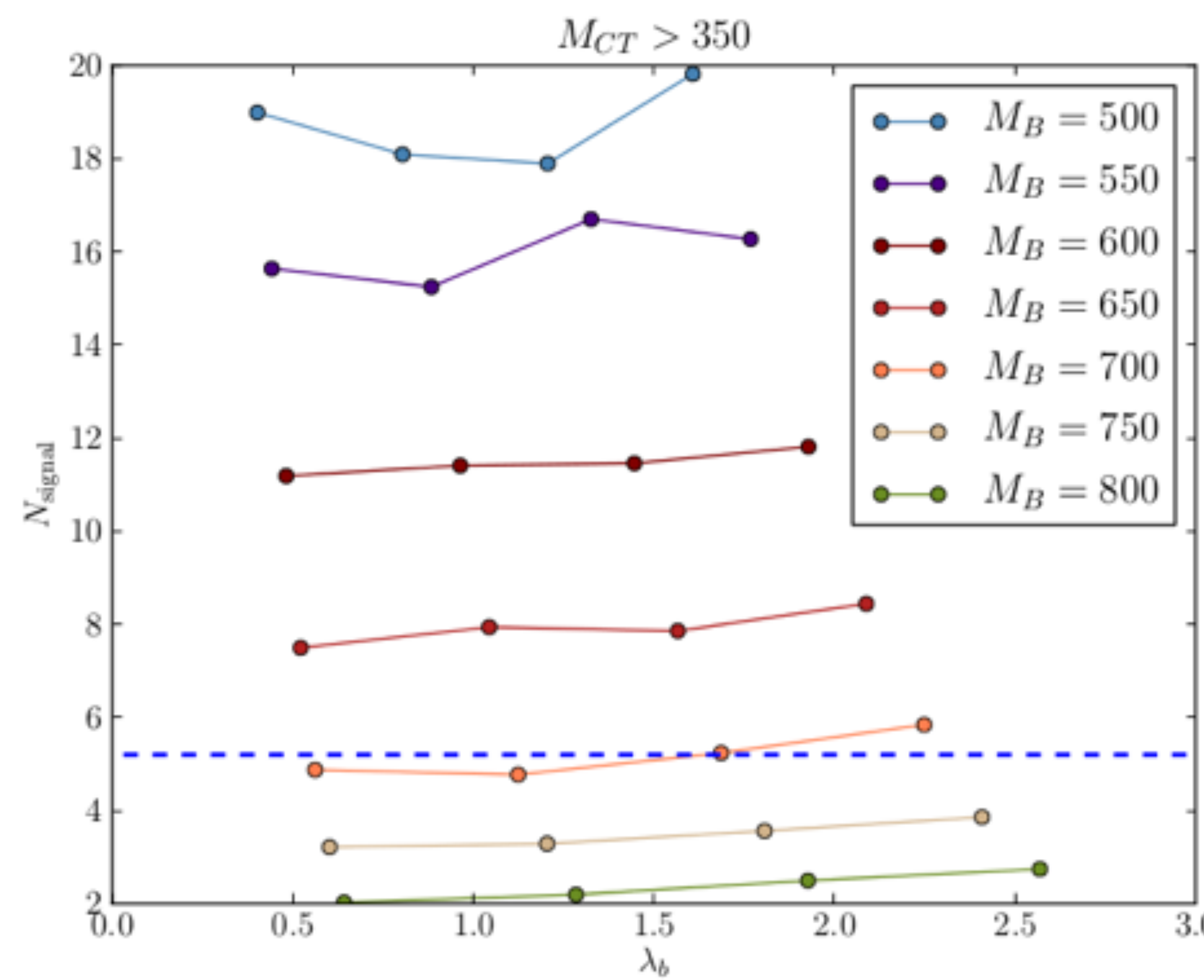
Because of large coupling, single production of mediator can also contribute:

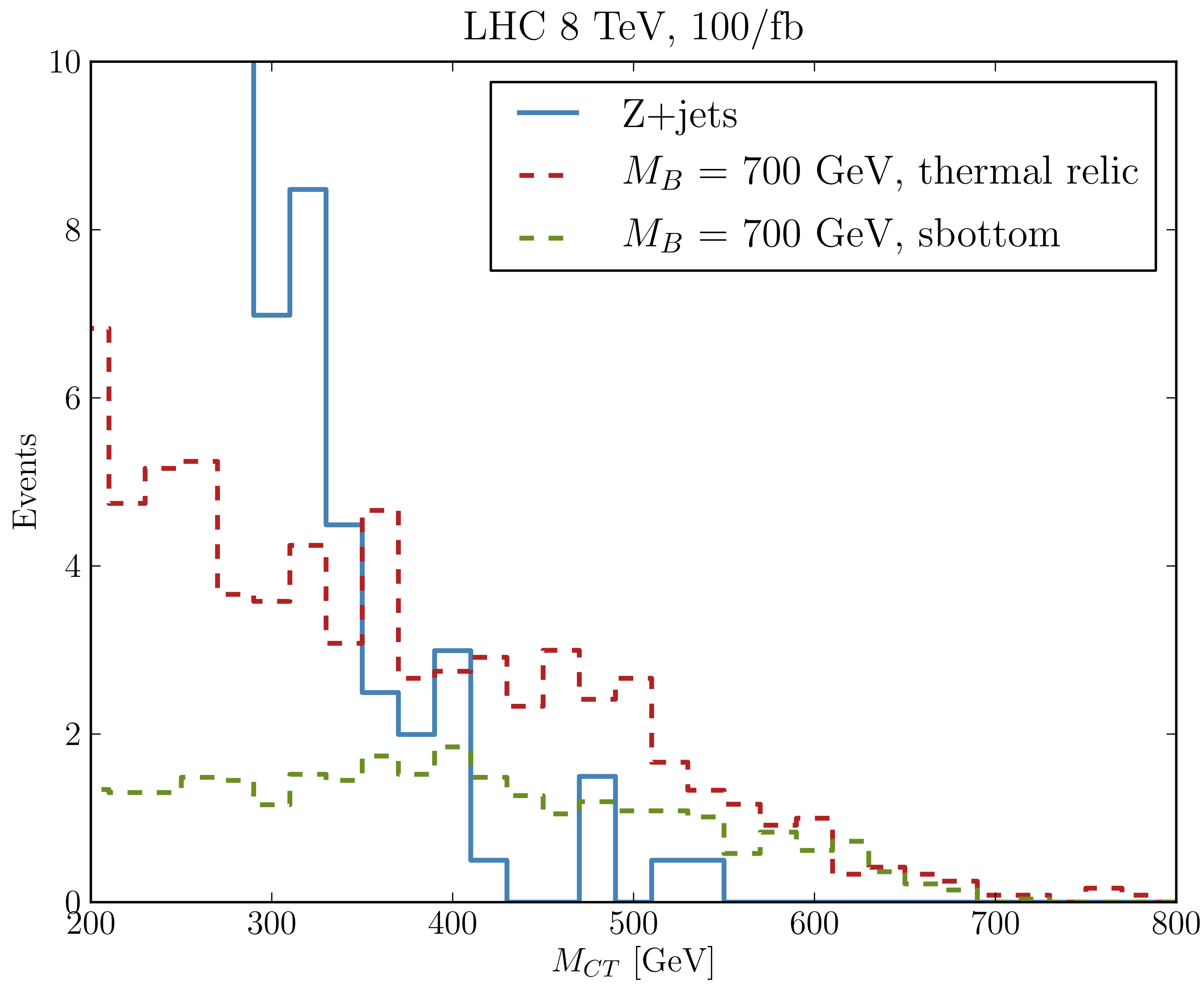




However, the spectrum in MCT is softer.

The final effect on the "sbottom search" limit appears to only be <10% in mediator mass.

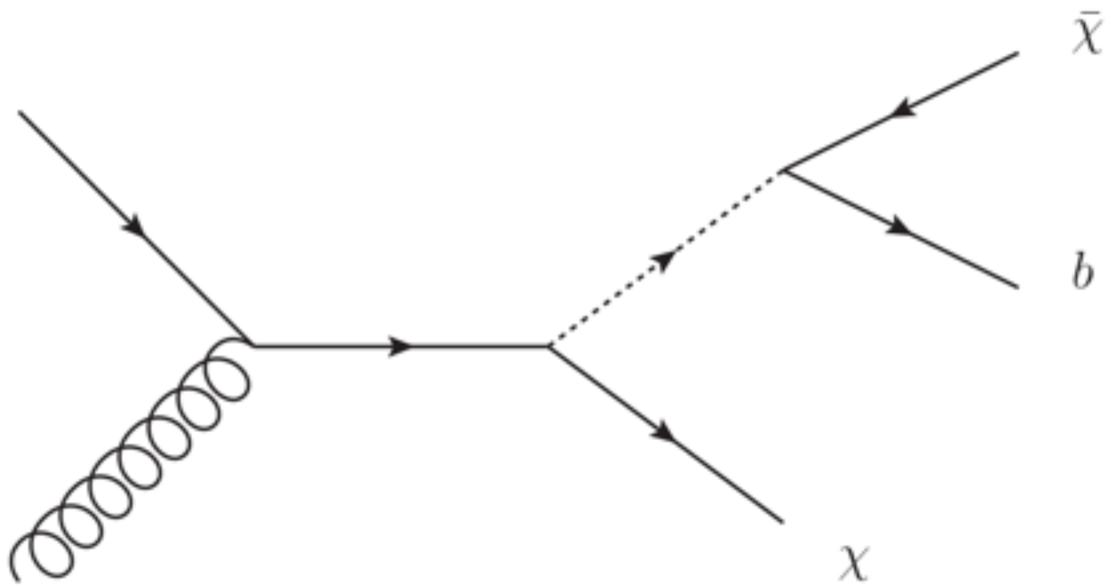




$$M_{CT}^2 = \left[E_T(j_1) + E_T(j_2)\right]^2 - \left[\vec{p}_T(j_1) - \vec{p}_T(j_2)\right]^2$$

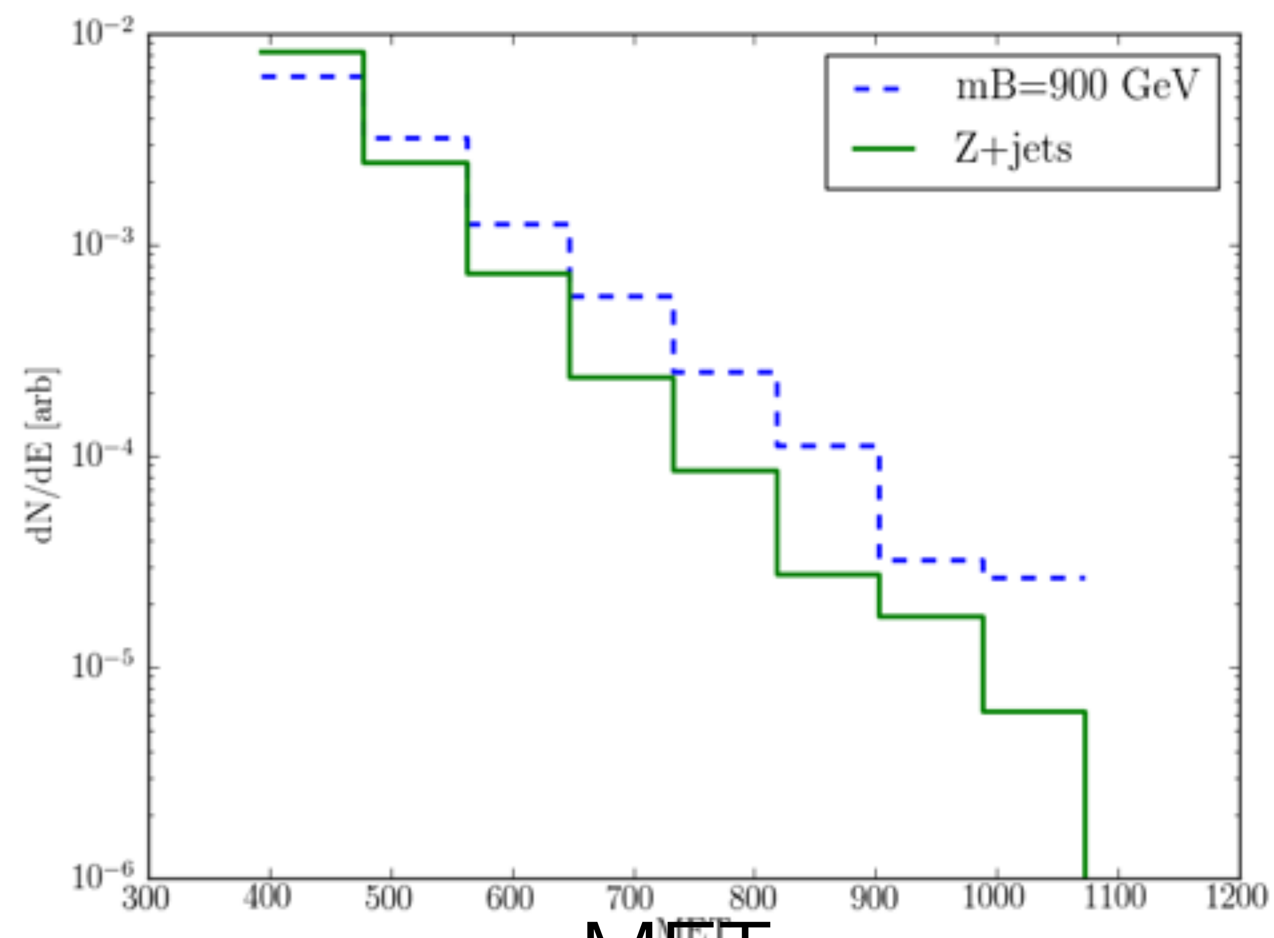
Single production of mediator:

“mono-b” final state with MET + *b*-jet, studied in Lin, Kolb, and Wang



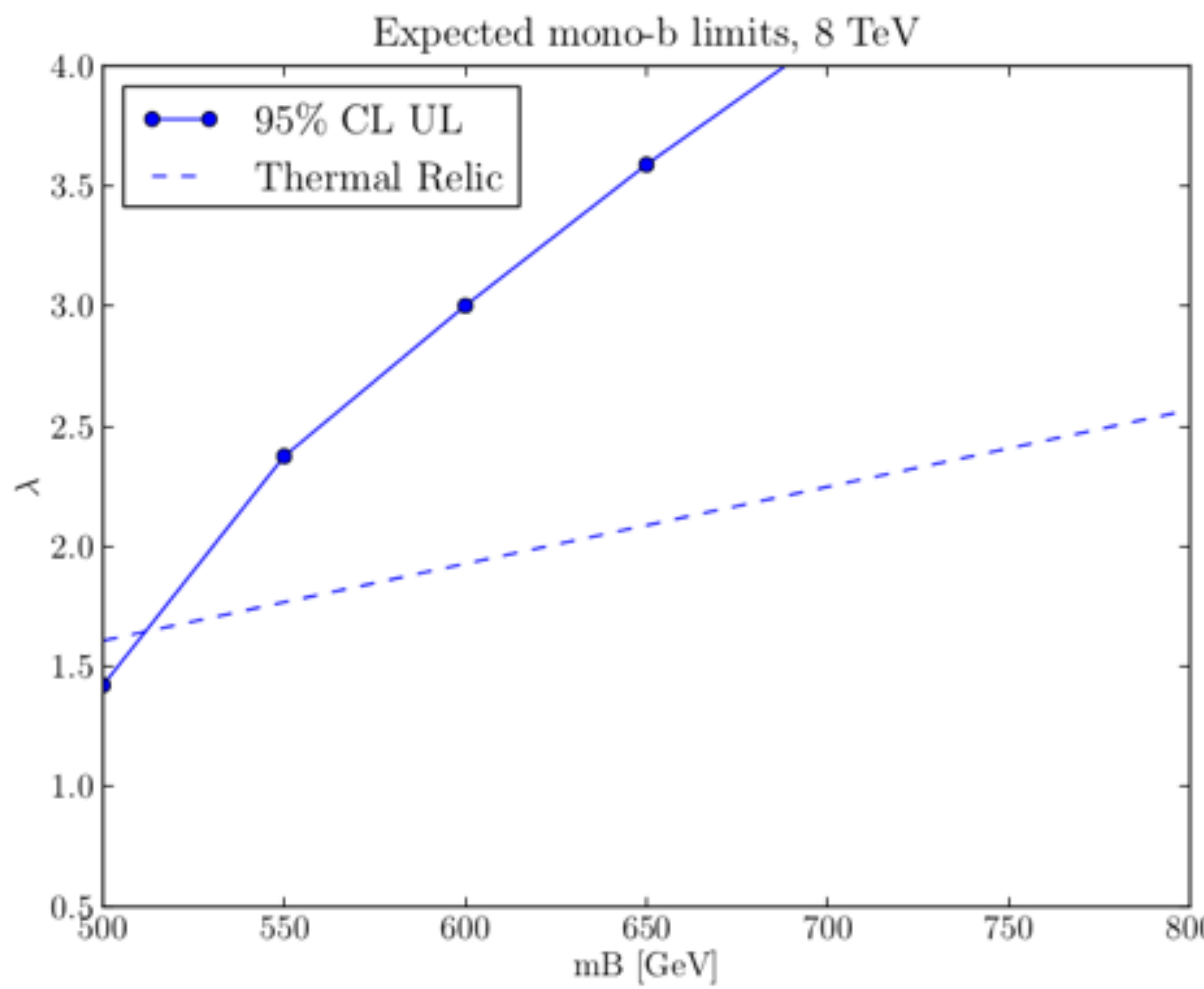
	Process	Monojet	b-tag	b-tag on j_1
Background	Z+jets(fake)	406 fb	11 fb	7 fb
	Z+b+jet	6.7 fb	4 fb	3 fb
	W+jets,W+b	95 fb	3 fb	2 fb
	$t\bar{t}$+jets	16 fb	11 fb	6 fb
Signal	$\bar{X}X$+jets	11 fb	0.9 fb	0.7 fb
	$\bar{X}X$ + b+jets	65 fb	40 fb	33 fb
	$\bar{X}X$ + $t\bar{t}$	244 fb	156 fb	113 fb

TABLE I: **Monojet and mono-b search at 8 TeV**



MET

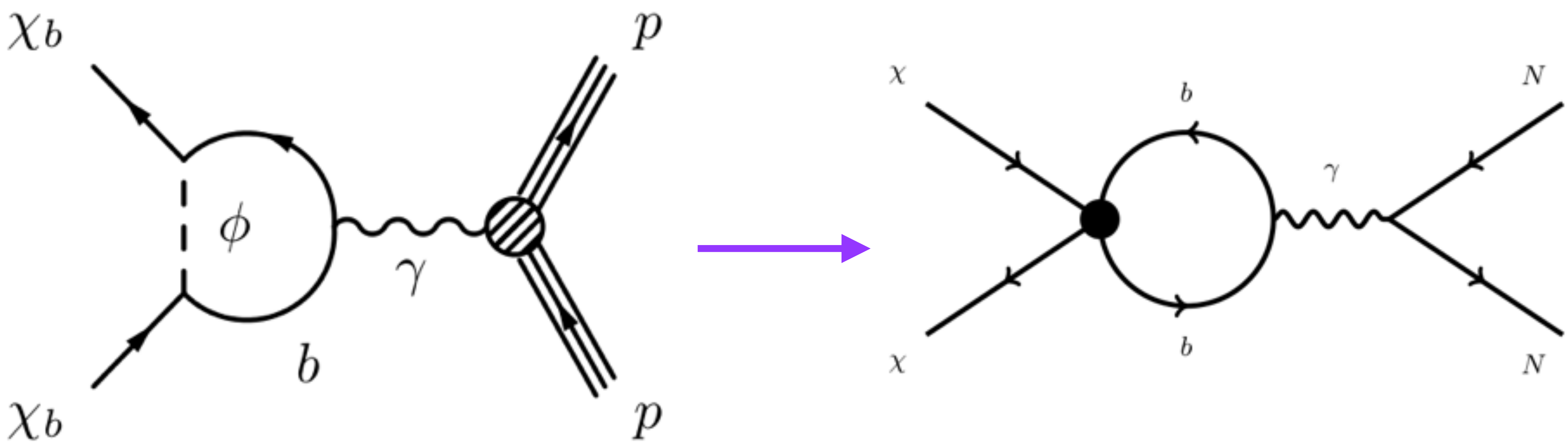
mono-b sensitive out to ~500 GeV in mediator mass:



Neither search was optimized for this model.

In discovery scenario, both mono-b and bb+MET channels could be used to distinguish the model from a sbottom.

direct detection



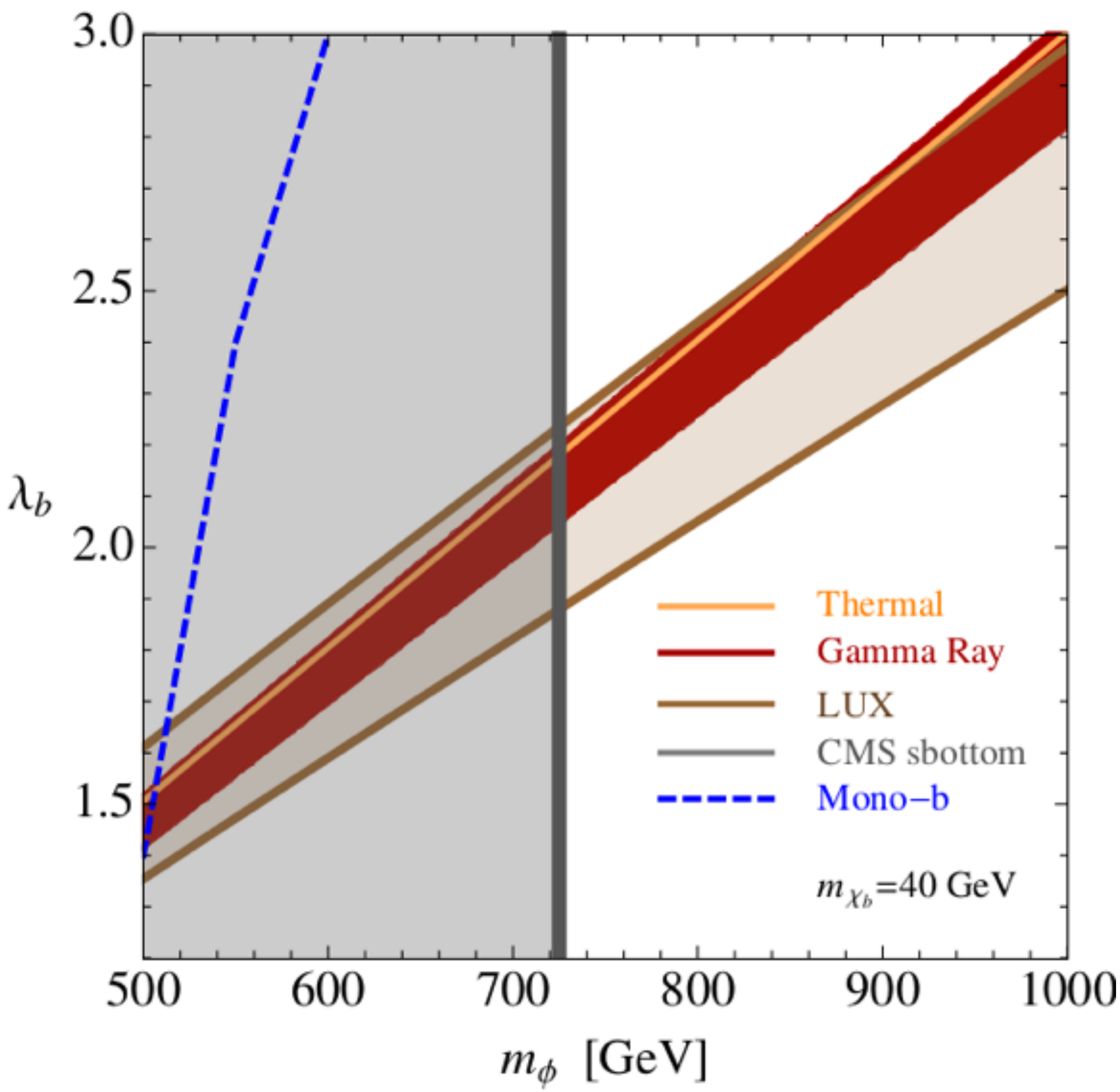
Charge-charge interaction:

$$\mathcal{O} \sim \frac{1}{m_\phi^2} \bar{\chi}\gamma^\mu \chi \partial^\nu F_{\mu\nu}$$

$$\mathcal{M} = b_q \bar{u}_\chi \gamma^\mu u_\chi \langle N | Q \bar{q} \gamma_\mu q | N \rangle \qquad b_q = -\frac{3 Q_b e \lambda_b^2}{64\pi^2 m_\phi^2}\left[1 + \frac{2}{3}\ln\left(\frac{m_b^2}{m_\phi^2}\right)\right]$$

$$\sigma_n \approx 10^{-45}\mathrm{cm}^2 \times \left(\frac{\lambda_b}{2.16}\right)^4 \left(\frac{725\ \mathrm{GeV}}{m_\phi}\right)^4$$

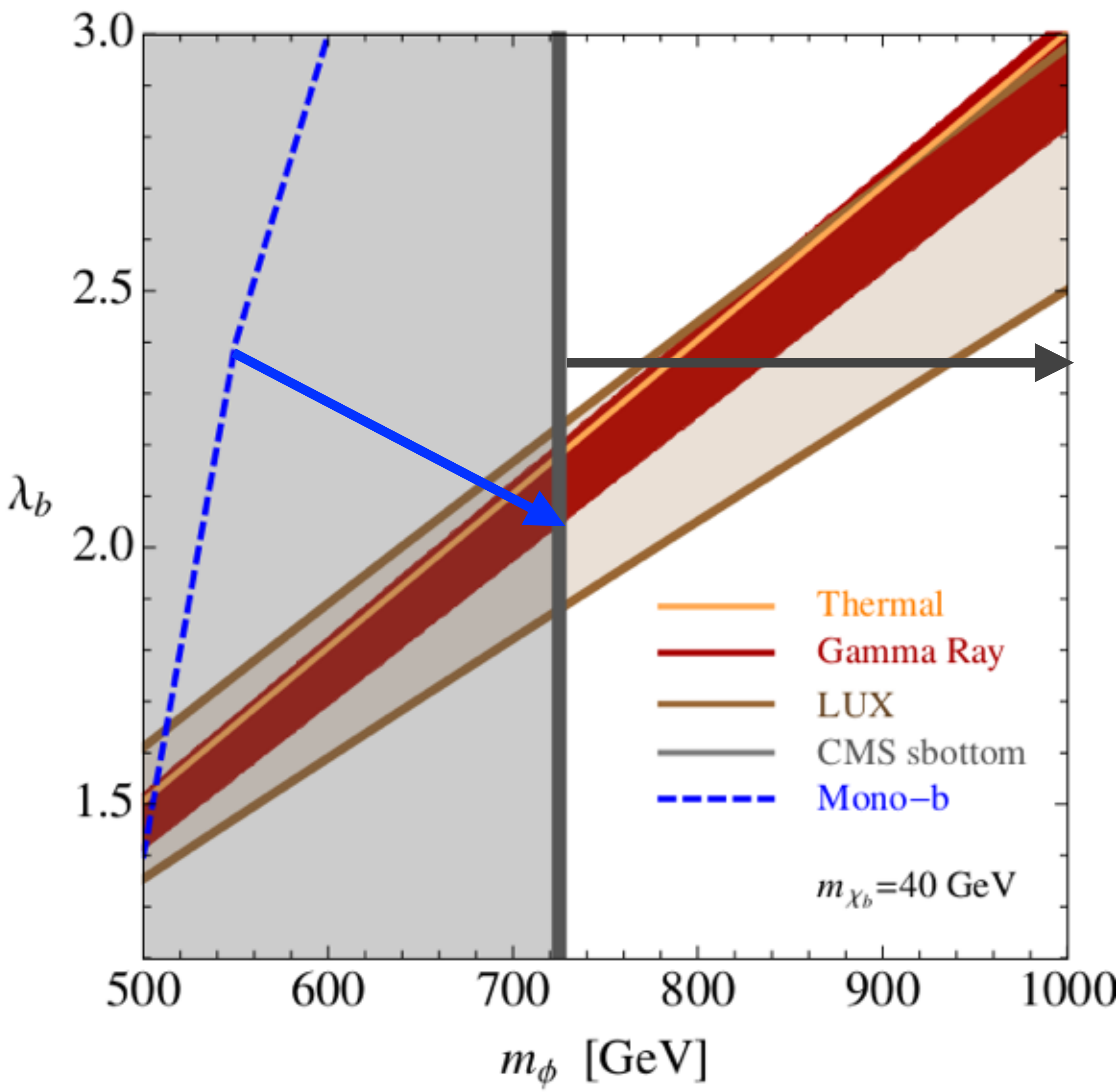
model prospects



parameter space:
large mediator mass,
large coupling needed

definitively tested by
increased LUX
exposure

model prospects



parameter space:
large mediator mass,
large coupling needed

mono-b, sbottom
searches with
LHC14, 100/fb

definitively tested by
increased LUX
exposure

conclusions

- flavored dark matter: natural setting for dark matter coupled to third generation quarks
- MFV dark matter - thermal relic for MFV SUSY, dark matter stability
- top and bottom flavored dark matter still alive but just within reach. bfdm also a model for GC gamma ray excess.